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PHYSICS OF TECHNOLOGY

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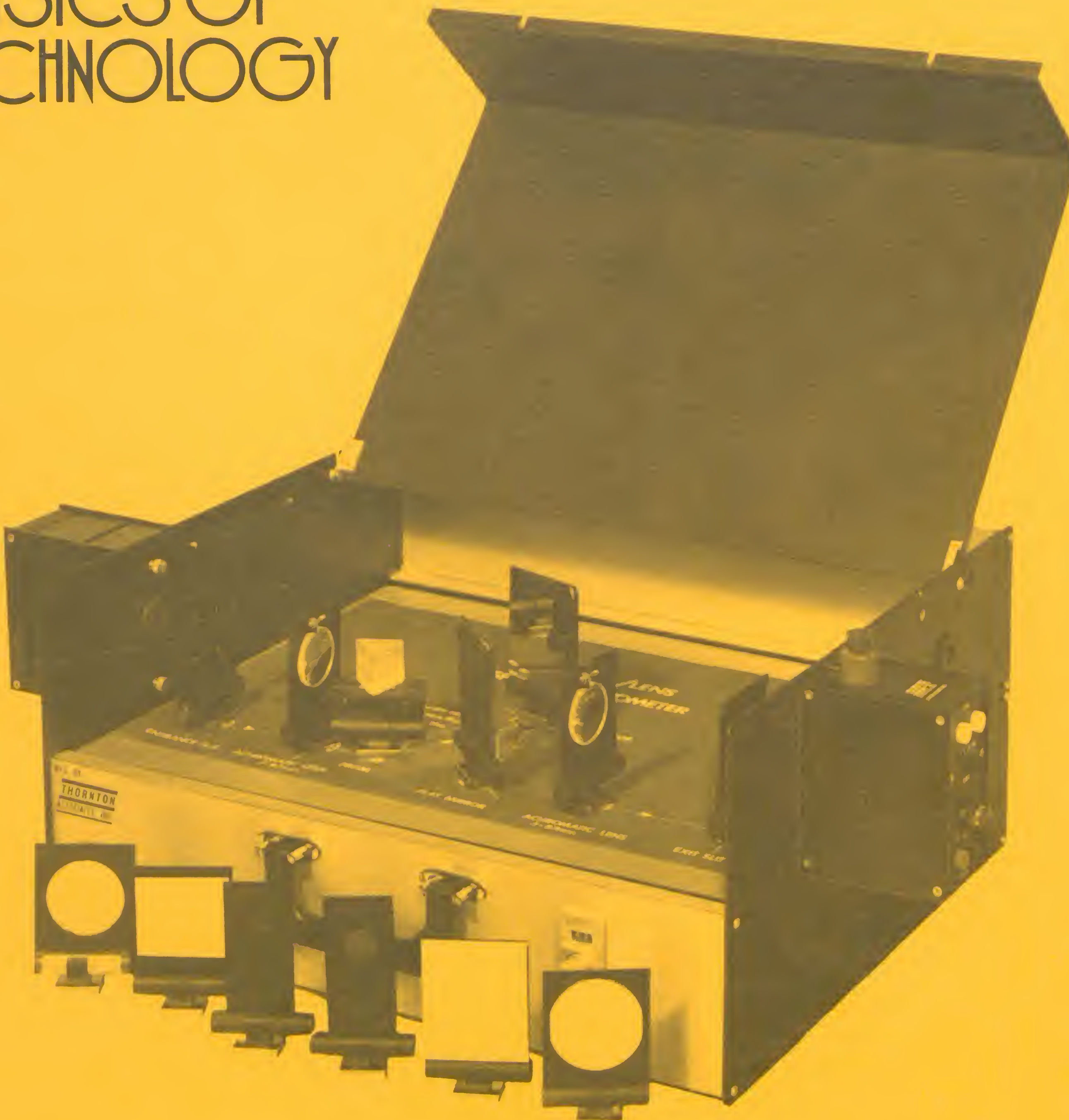

THE SPECTROPHOTOMETER

The Spectral Properties of Light

THE SPECTROPHOTOMETER

A Module on the Spectral Properties of Light

TERC

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MCGRAW-HILL BOOK COMPANY

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The Physics of Technology modules were produced by the Tech Physics Project, which was funded by grants from the National Science Foundation. The work was coordinated by the American Institute of Physics. In the early planning stages, the Tech Physics Project received a grant for exploratory work from the Exxon Educational Foundation.

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This module was written and tested at the Curriculum Development Laboratory of the Technical Education Research Centers, Inc.

The authors wish to express their appreciation for the help of many people in bringing this module to final form. The criticisms of various reviewers and the cooperation of field-test teachers have been most helpful. Several members of the staff of the Technical Education Research Centers also deserve special recognition for their contributions. They are:

Richard R. Lewis . . . . Apparatus Design
Mary A. Heffernan . . . . Graphic Composition
John W. Saalfield . . . . Illustration

In addition, special thanks go to our physics consultants:

Nathaniel H. Frank, Massachusetts Institute of Technology
Ernest D. Klema, Tufts University

Cover photograph courtesy of Thornton Associates, Inc.

The Spectrophotometer

ISBN 0-07-001731-X

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PREFACE

ABOUT THIS MODULE

Its Purpose

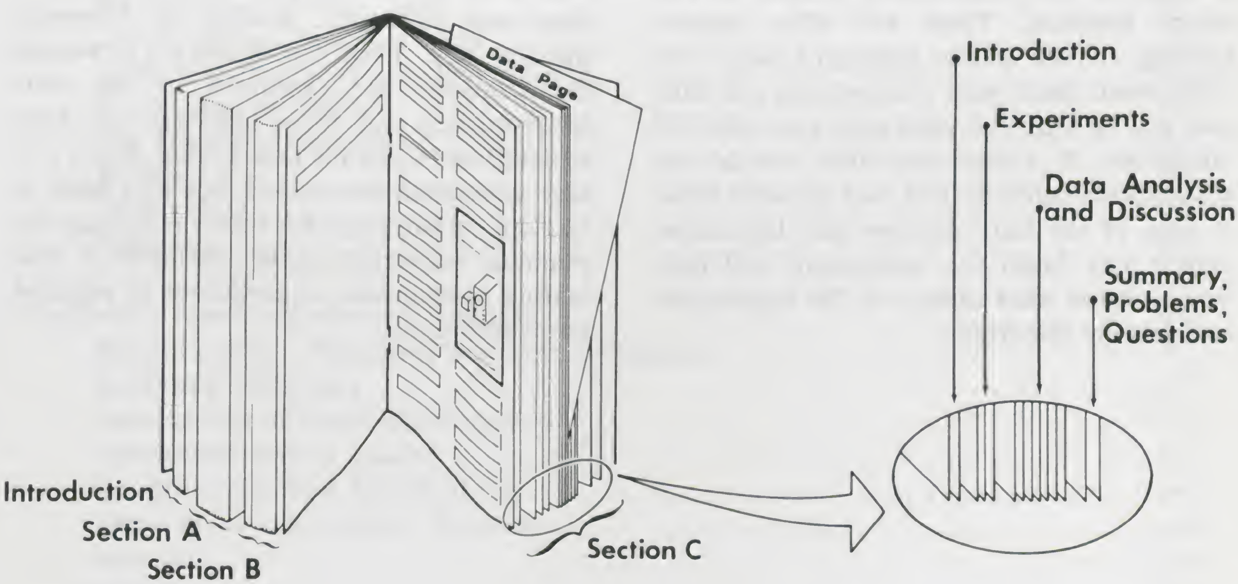
The purpose of the Physics of Technology program is to give you an insight into some of the physical principles that are the basis of technology. To do this you are asked to study various technological devices. These devices have been chosen because their operation depends on or illustrates some important physical phenomenon. In this module the device is the spectrophotometer. Its design and use are based on the spectral properties of light.

The PoT program has adopted a modular format with each module focusing on a single device. Thus you can select those modules that relate to your own interests or areas of specialty. This preface highlights some of the features of the modular approach so that you may use it efficiently and effectively.

Its Design

The module design is illustrated below. The *Introduction* explains why we have selected the spectrophotometer to study and what physical principles will be illustrated in its behavior. Learning *Goals* are given, as well as *Prerequisite* skills and knowledge you should have before beginning. The three *Sections* of the module treat different aspects of the device. They are of increasing difficulty but each can be completed in about one week.

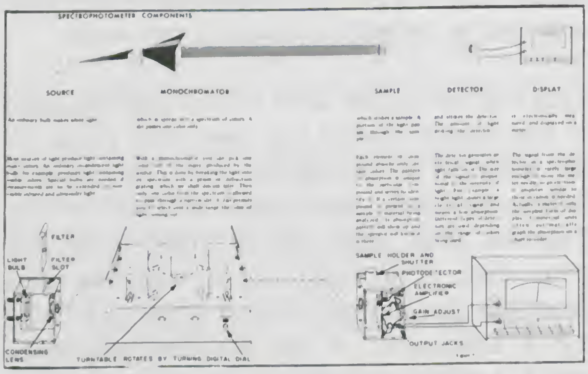
Each section begins with a brief *Introduction* to the topics treated and how they relate to the behavior of the device. The *Experiments* follow and take about two to three hours. Tear-out *Data Pages* are provided to record your data. The body of the section then describes the method of *Data Analysis* including a *Discussion* of the physical principles which explain your results. A *Summary* ends the section with *Problems* and *Questions* you can do to test your understanding.



HOW TO USE THIS MODULE

To Begin

This module has been written so that it can be quickly and easily scanned. That is, you can get the gist of the ideas and experiments by simply flipping from page to page, reading only the headings and italicized words, and looking at the illustrations. We suggest before you begin a section or an experiment that you scan through it in this way so that you will know where you are going.

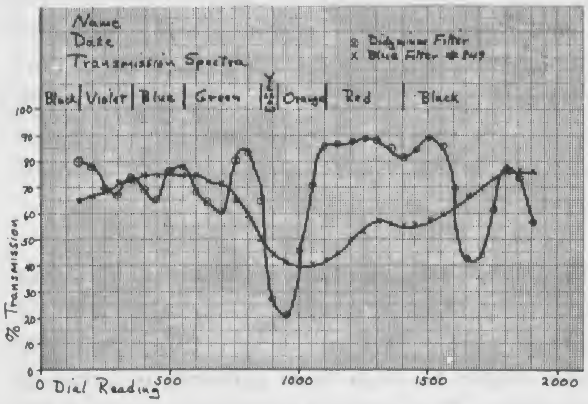


The Experimental Activities

The heart of the Physics of Technology modules is the experimental studies of the device behavior. These will often involve learning to use a new measuring device or instrument. Since your observations and data may not be analyzed until *after* you leave the laboratory, it is important that you do the experiments carefully and take accurate data. A scan of the Data Analysis and Discussion *before* you begin the experiment will help you to know what aspects of the experiment and data are important.

The Data Analysis

The data you take will generally have to be graphed before they can be analyzed. Graphing and graphical analysis are essential parts of experimental science. And understanding graphs is important for technology since technical information is often presented graphically. For these reasons, and since the discussion of your results will be centered around your graphs, it is important that you prepare them clearly and accurately.



Review

When you finish a section you should again scan it to be sure you understand how the ideas were developed. Reading the *Summary* will also help. Then you should try to answer the *Problems* and *Questions* to test your understanding and to be sure that you have achieved the *Goals* for that section. When you have completed the module, you may want to tear out certain pages for future reference; for example, conversion tables, methods of calibrating instruments, explanations of physical terms and so on.

TABLE OF CONTENTS

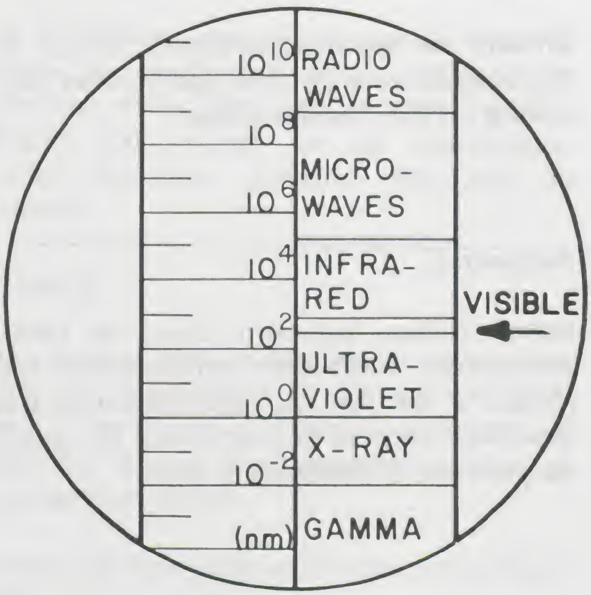
The Spectrophotometer

INTRODUCTION: Why Study Spectrophotometers?

THE PHYSICS HAS MANY APPLICATIONS

In order to really understand how a spectrophotometer works and is used, you will have to learn about light—how it is produced, measured, controlled, and detected—and about color. One frequently comes in contact with the principles involved and in applications quite different from spectrophotometers.

The light that we see with our eyes, *visible light,* is only a small part of a more general kind of radiation called *electromagnetic radiation.* Other types of electromagnetic radiation include radio waves, microwaves, x-rays, gamma rays, infrared, and ultraviolet radiation.



ELECTROMAGNETIC SPECTRUM

Figure 1.

The spectrophotometer you will use can make use of not only visible light but also the two types of electromagnetic radiation—infrared and ultraviolet—that you cannot *see.*

Visible light, ultraviolet, and infrared radiation are all present in common sources of light: flames, light bulbs, fluorescent lamps, and the sun. However, if one wishes to separate out the different kinds of radiation from a light source, a prism or other separator is required. Such separators are called *dispersive elements* and they are the key components in spectrophotometer design.

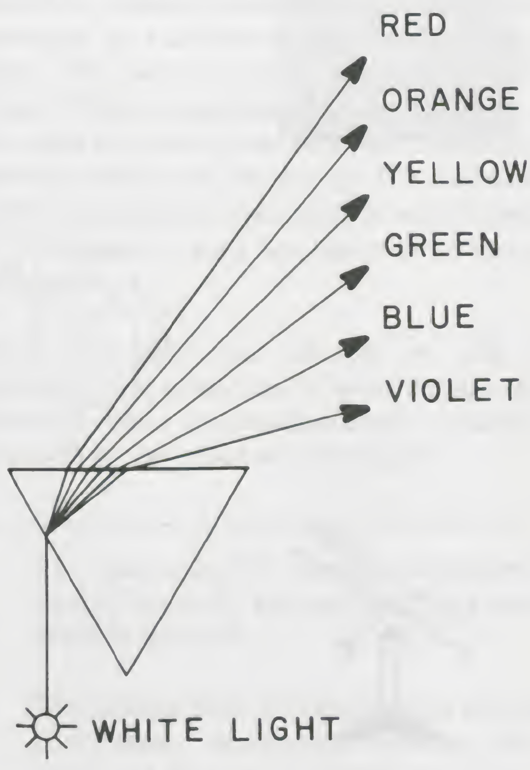


Figure 2.

Other instruments, called *spectrometers,* are used to study the other types of electromagnetic radiation (gamma-ray spectrometers, x-ray spectrometers, etc.). These other spectrometers have most of the same basic components that you will study here. Thus, the principles that you will learn in your study of the spectrophotometer are useful for many other applications.

SPECTROPHOTOMETERS ARE WIDELY USED

There are many areas in industry, medicine and science where spectrophotometers, or devices which work on the same principles, are used. The following examples indicate the widespread use of such instruments.

Figure 3.

Medicine

Spectrophotometers are routinely used to analyze body fluids to help spot disease before it becomes serious. For example, a standard test for diabetes uses a spectrophotometer to measure the sugar level in urine.

Pollution Control

The widespread use of powerful insecticides and pesticides creates an increasing threat of poisoning ourselves and our water. Scientists use spectrophotometers to find trace amounts of these toxic compounds before they cause harm.

Beer Production

Brewers use spectrophotometers instead of tasters to monitor the color and flavor of beer coming off the production line.

Astronomy

Before helium had been found on earth, astronomers using spectrophotometers had located it on the sun. Spectrophotometers have been essential in determining the speed, size, and age of thousands of stars.

Law Enforcement

Police laboratories use spectrophotometers to identify poisons which are difficult or impossible to tag any other way. Narcotics and sleeping pills are examples. Race tracks run routine tests with spectrophotometers to check whether horses have been drugged.

WHAT WILL YOU LEARN?

SECTION A: Measuring Light Absorption

In the first part of the module you will put together a very simple spectrophotometer using your eye to detect the light. You will see how various materials absorb visible light differently, and that two materials that may look alike to the eye have quite different light transmission (or absorption) properties. You will learn that *transmission spectra* are central to the way in which spectrophotometers are used in analysis.

Visible light is only one type of a broad class of *electromagnetic radiation.* Two other types, ultraviolet and infrared, are also used by spectrophotometers. Since these types of radiation cannot be seen, a method other than "color" is required to specify them. You will learn about *wavelength* specification for electromagnetic radiation.

SECTION B: The Dispersion of Light

In the second part of the module you will study the components used to separate, or disperse, white light into its various colors. Prisms and gratings are the components, called *dispersive elements,* that will be studied. These components depend on different optical principles to disperse the light and therefore they act differently. You will observe the behavior of the dispersive elements and see their differences. You also will learn to describe and explain their behaviors in terms of the wavelike properties of light.

Finally, you will assemble a good quality spectrophotometer system that will let you detect nonvisible ultraviolet and infrared radiation.

SECTION C: Spectrophotometer Analysis

In the third part of the module you will use the spectrophotometer you assembled in Section B to measure accurately the transmission spectrum of a *didymium* (di-dim′-ē-um) glass filter. This will introduce you to the techniques of spectrophotometric analysis and, at the same time, show you how spectrophotometers are calibrated. Didymium is a substance whose transmission spectrum is well known. It is commonly used for spectrophotometer calibration.

From your data you will also be able to determine the *resolution* of your instrument. This and other spectrophotometer specifications will be described and discussed.

GOALS

The general goals of this module are to give you an understanding of the nature of light, and a knowledge of how the properties of light are used in the design and operation of spectrophotometers.

Achieving these goals will involve a knowledge of:

1. The wave description of light and its application to infrared, visible, and ultraviolet radiation.
2. The term used to describe colors of light (wavelength).
3. The graphs used to display the transmission of colors by various materials (transmission spectra).
4. The devices used to disperse light into its component wavelengths (prisms, gratings), and the physical processes (refraction, diffraction) on which each depends.
5. The operating principles of spectrophotometers, including the purpose of each of its basic components, the methods used for calibration, and the procedures for making qualitative analyses.

SECTION A

Measuring Light Absorption

WHAT IS A SPECTROPHOTOMETER?

The light from an ordinary light bulb is actually a mixture of many colors. When *white light* is separated into its component colors the result is called a *spectrum.* This is where the "spectro" part of the name spectrophotometer comes from.

Photometer means light meter or light-measuring device. Thus, a spectrophotometer is a device which measures the light spectrum of something.

Why Is It Used?

A spectrophotometer is used to answer questions about how light is affected by substances. Light can be reflected from, absorbed by, or transmitted through materials. But the fraction of the light reflected, absorbed, or transmitted by a particular material depends on the *color* of the light.

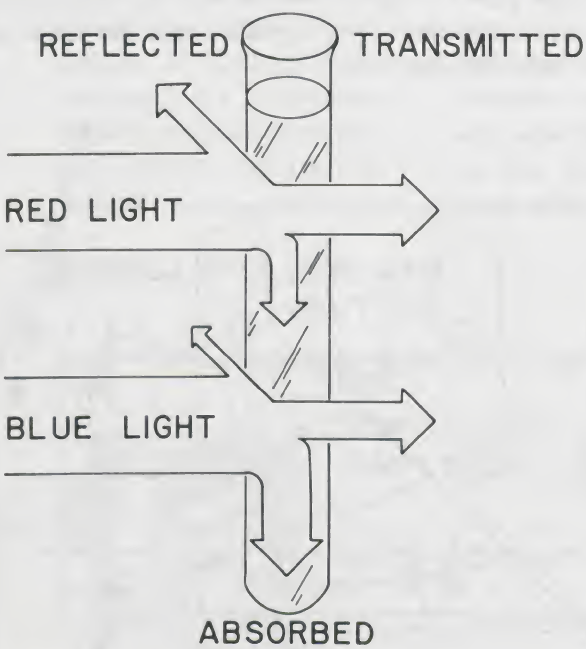


Figure 4. In the same liquid in a test tube, the amounts of reflected, absorbed and transmitted light differ for different colors.

Different chemical substances have unique patterns of absorption and reflection. These patterns are like fingerprints, since they can be used for identification. To do this identification a spectrophotometer can measure the amount of each color of light which is reflected, transmitted, or absorbed by a sample.

Thus, with a spectrophotometer you can find out *what* substances are present in a sample of material (*qualitative analysis*) and *how much* (*quantitative analysis*), just by passing light through it.

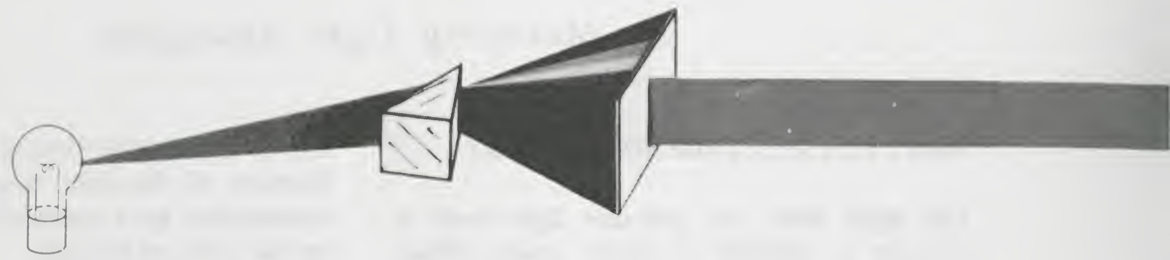
How Does It Work?

There are five major parts to every spectrophotometer:

1. The *light source,* which produces light with many colors in it
2. A *monochromator,* which selects one color from the source
3. A *sample,* where part of the light is absorbed
4. A *detector,* which converts the transmitted light into an electrical signal
5. A *display unit,* which records the light level

The figure on the next two pages shows each of these components in the student spectrophotometer that you will use.

SPECTROPHOTOMETER COMPONENTS



SOURCE

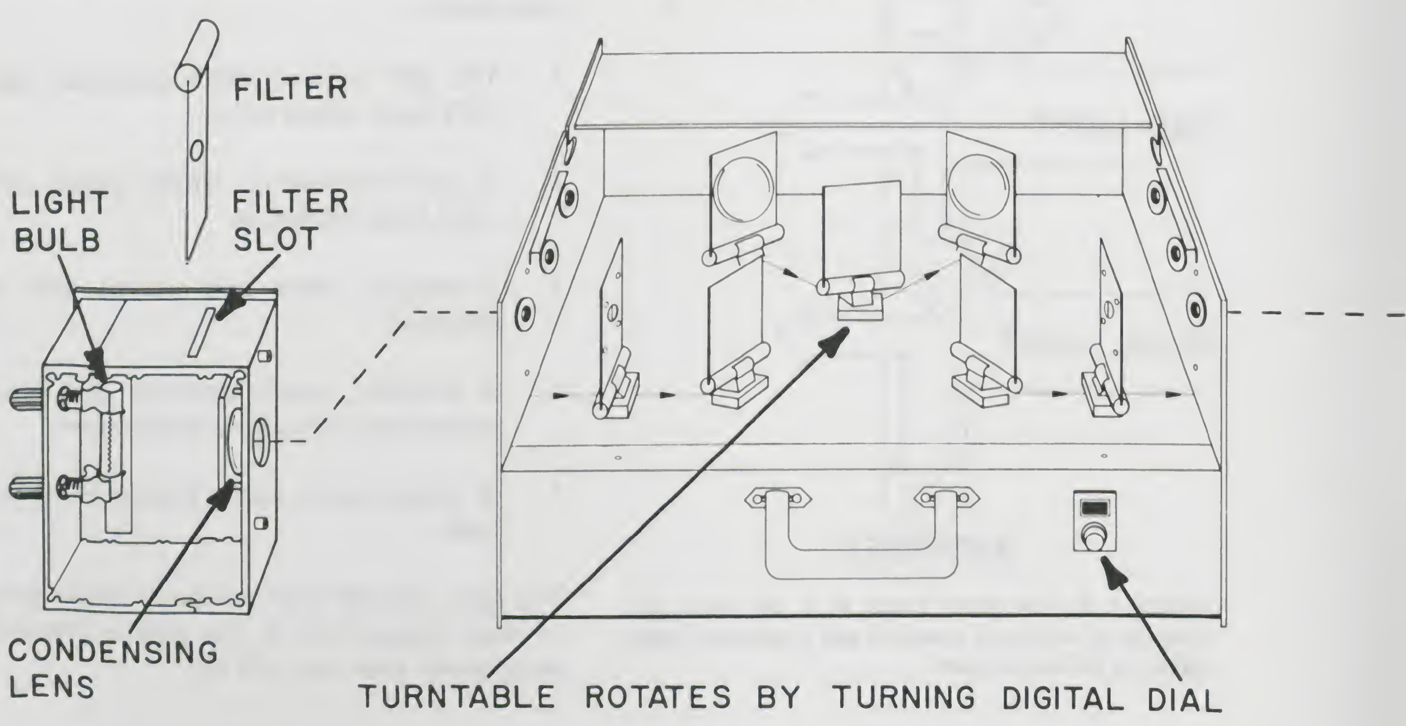
An ordinary bulb makes white light. . .

Most sources of light produce light containing many colors. An ordinary incandescent light bulb, for example, produces light containing visible colors. Special bulbs are needed if measurements are to be extended to non-visible *infrared* and *ultraviolet* light.

MONOCHROMATOR

which is spread into a spectrum of colors. A slit passes one color only. . .

With a monochromator you can pick one color out of the many produced by the source. This is done by breaking the light into its spectrum with a prism or diffraction grating, which we shall discuss later. Then only one color from the spectrum is allowed to pass through a narrow slit. A dial permits you to select over a wide range the color of light coming out.



which strikes a sample. A portion of the light passes through the sample. . .

and strikes the detector. The amount of light striking the detector. . .

is electronically measured, and displayed on a meter.

Each element or compound absorbs only certain colors. The pattern of absorption is unique to the particular compound and serves to identify it. If a certain compound is present in a sample of material being analyzed, its absorption pattern will show up and the operator will know it is there.

The detector generates an electrical signal when light falls on it. The size of the signal is proportional to the intensity of light. For example, a bright light causes a large electrical signal and means a low absorption. Different types of detectors are used, depending on the range of colors being used.

The signal from the detector in a spectrophotometer is rarely large enough to move the meter needle, so an electronic amplifier, similar to those in radios, is needed. Actually, a meter is only the simplest form of display. Commercial units often automatically graph the absorption on a chart recorder.

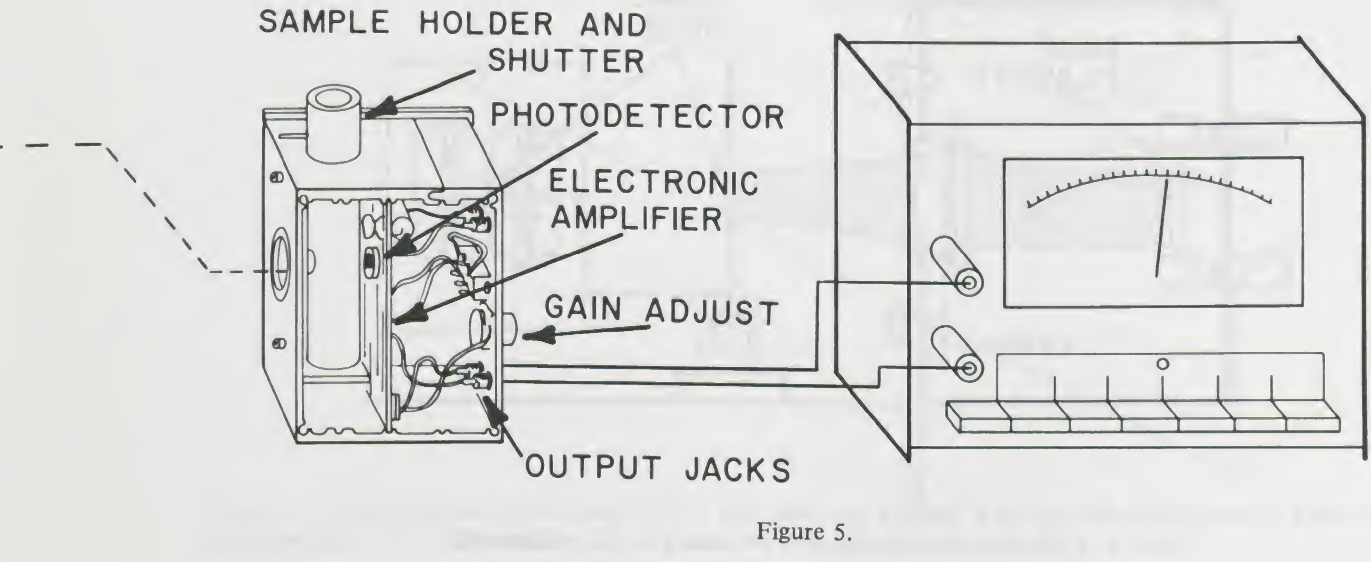


Figure 5.

SPECTROPHOTOMETER COMPONENTS

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DETECTOR

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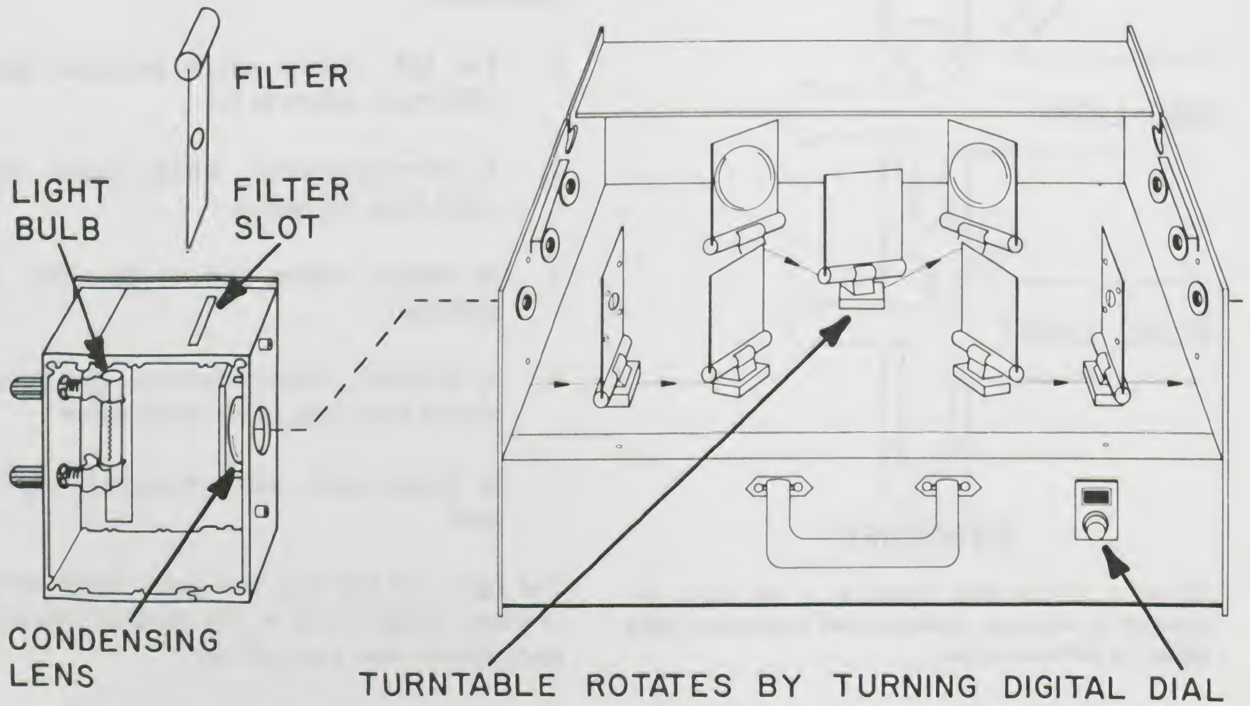


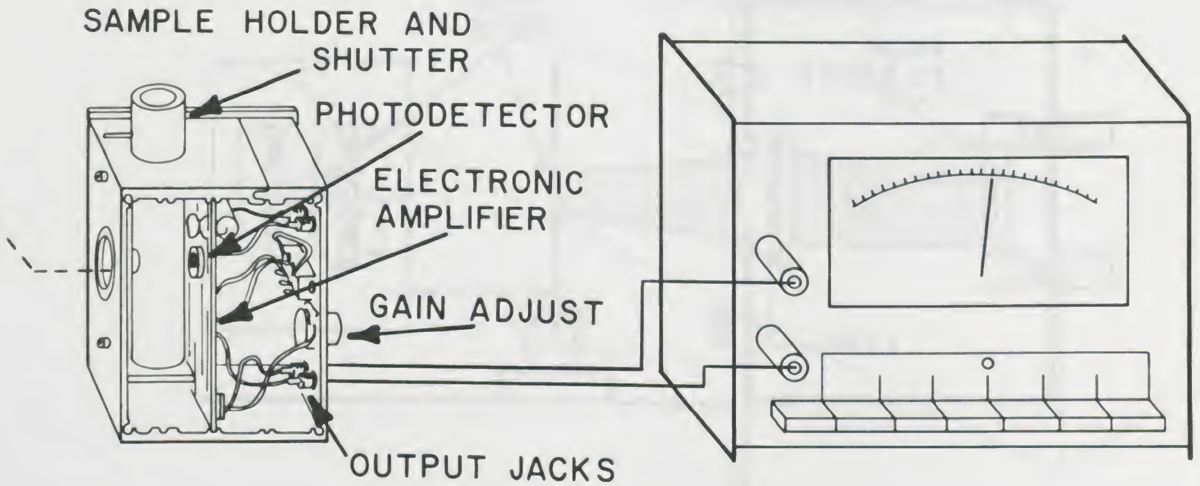


Figure 5.

EXPERIMENT A-1. The Light Source

A basic part of any spectrophotometer is the source of light. The light produced should be very bright and include a broad range of colors. In your spectrophotometer, the source is a high-intensity incandescent lamp, similar to those used in automobile tail lights. The white light it produces includes all of the visible colors.

In order to increase the brightness, a lens is used to gather as much of the output of the bulb as possible and concentrate it on the entrance slit. This means that one must focus the light to form an *image* of the bulb filament. The image should just fill the slit through which the light enters the main part of the spectrophotometer (entrance slit).

Setting Up

1. *Inspect the light-source box.* Open it up and observe the arrangement of the bulb and the lens. Note in particular the bulb filament. It should be long and straight.

2. *Attach the light-source box securely* to the monochromator table so that the light shines through the entrance hole nearest you on the left.

3. *Turn on the light source.*
   CAUTION: Do not look directly at the filament; the light is extremely intense.

Imaging the Filament

1. *Place the entrance slit* on the monochromator table with the black side toward the light.

2. *Move the slit around* (back and forth and side to side) until you get the sharpest possible image of the filament *centered on* and *passing through* the slit. If it is not centered vertically, ask your instructor for help to make a further adjustment.

3. *Place the white card* after the entrance slit and observe the light coming through the slit. Make fine adjustments of the slit until the light is centered and uniformly bright on the card.

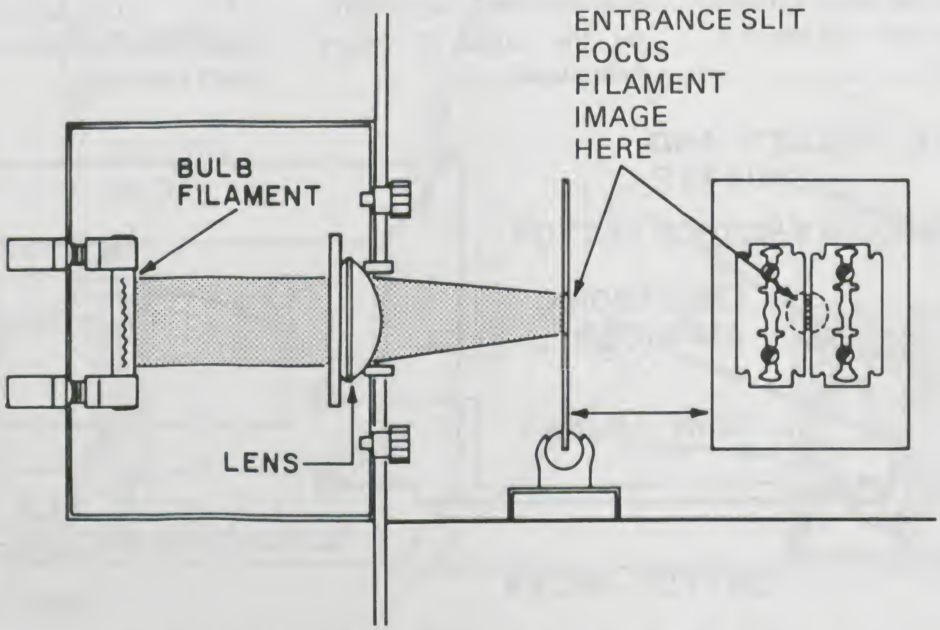


Figure 6. Light from the bulb filament is focused on the entrance slit.

You can now make a simple spectrophotometer with your laboratory apparatus. For a first attempt you will make one which illustrates the principles, but is too inaccurate for practical use. That is because you will use your eye in place of the detector and meter. You will simply look at a spectrum and estimate how much of each different color is in the spectrum. You may be surprised how well you can estimate with practice.

CAUTION: Three Things to Watch Out For

1. *Front surface mirrors.* Common mirrors have silver behind glass to protect the silver. But the mirrors in this apparatus have silver in front of the glass to improve their quality. It is very easy to scratch off the thin layer of silver. **Don't** put them face down and **don't** touch the mirror surface. If you see that a mirror is dirty **don't** try to clean it. Improper cleaning can scratch the surface badly.

2. *Diffraction grating.* A diffraction grating also has a delicate front surface. The same precautions apply to gratings as to mirrors. Those precautions are even more important because some gratings are extremely expensive.

3. *General care.* This experiment uses delicate scientific equipment. Treat it all with care. The prisms can chip and the mirrors can break. The lamp and detector are both fragile and can break or become misaligned. Please be careful.

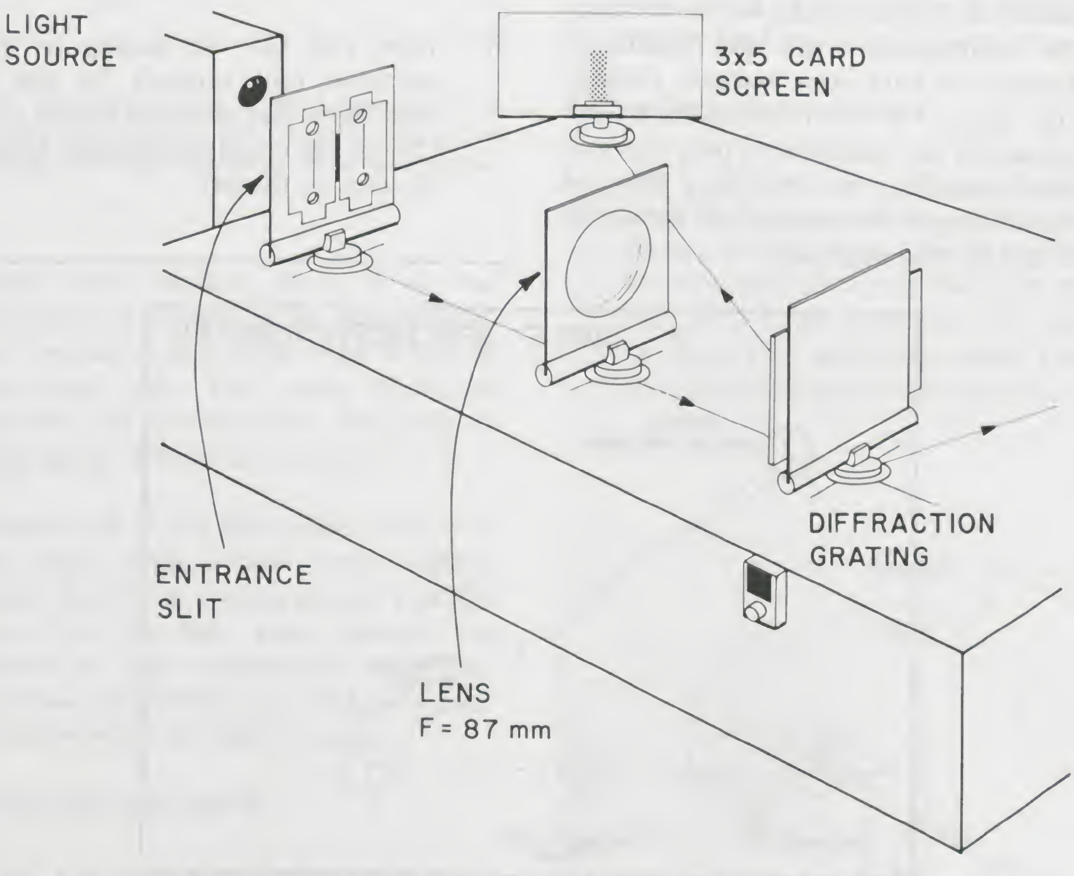


Figure 7. A spectrophotometer using only a slit, lens, and grating. It spreads the light from the source into a spectrum on a 3 X 5 index card.

SETTING UP A GRATING SPECTROPHOTOMETER

1. *Place the template* titled A SIMPLE SPECTROPHOTOMETER securely on the base, centered on the turntable.

2. *Place the components on the base* as shown in Figure 7 and the plan below. When you do this, you should see the colors of the rainbow in a spectrum on the white 3 X 5 index card. You may have to make some adjustments to make it work best. This procedure is called *alignment.*

Alignment

1. *Follow the checklist on this page* for the details of aligning the other components. Every time you set up the optical system you have to fuss with it to make it work well. The general idea is to start at the source and adjust (slide, tilt, and rotate) the components until the maximum amount of light goes squarely through the center of each component. The circles on the template are only *approximate* positions, so you may have to move components *slightly* off the circles to get the best alignment.

Alignment Checklist

A. You want as much light as possible to pass through the first slit. Move the slit around until the *brightest* and *smallest* possible line of light from the source passes through the center of the slit as in the previous experiment.

B. You also want the lens to focus the most light possible. Find the beam of light coming from the slit by letting it hit another 3 X 5 index card you hold. See Figure 9. Make sure that the lens is in the center of this beam. If it isn't, slide it sideways into the center, but do not move it any closer to the slit.

C. Slide the grating so that it also is in the center of the light beam, but do not move it any closer to the lens.

D. Turn and tilt the grating so that a *spectrum* falls squarely on the white card. Note that there are several spectra. Choose the brightest spectrum which has the blue on the left.

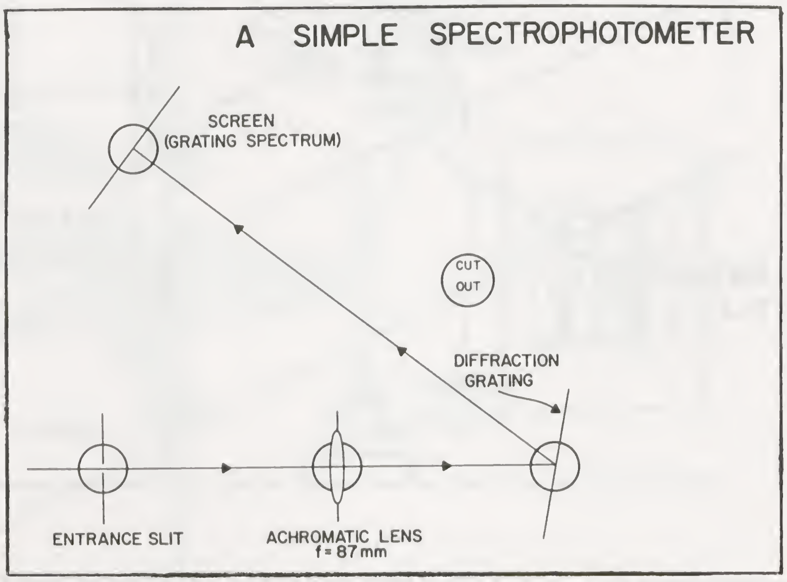


Figure 8. The layout of the grating spectrophotometer, showing the light path to use. When setting up the experiment, it is important to use approximately the angles and distances shown.

Before using your spectrophotometer, be sure you know where the light is going. The light starts in the source box. It then goes through the slit, the lens, and strikes the grating. The light leaves the grating in several beams. One beam is reflected as white light, but each of the others is broken into a spectrum of colors. These spectra decrease in brightness the greater the angle they make with the white refelction. You should have one of the two brightest ones on the screen.

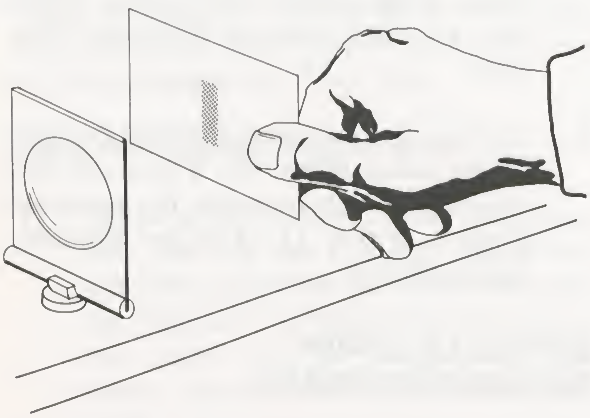


Figure 9. The beam can be followed from source to screen using this method. The maximum amount of light should be transmitted by each component.

2. *Light some incense,* place it on the incense holder, put it in the box, and put on the clear plastic cover to get a view of the light path. The smoke from the incense will let you "see" the paths of light going through the system.

   Observe all of the light paths. Note that the light paths appear more brilliant when the light is coming toward you. Do you have the light going through the center of each component? Make any necessary corrections by using the smoke to show where the light is going.

Observing Light Absorption

Now that you have set up the instrument, what can you do with it? One use is to look at the effects of colored filters on the spectrum. You should have a pack of plastic filters with your equipment.

1. *Find out the effects of various filters* on light by placing them one at a time, in the light path near the slit. You will find that the darker filters have more noticeable effects. Does it matter where you place the filter in the light path? Do you get the same result by looking through the filter at the spectrum? Why?

2. *Try the didymium filter,* a pale-blue glass filter. This filter fits into a slot in the source box.

   Notice that the didymium filter removes almost all of the yellow light from the spectrum. We say that this filter *absorbs* yellow. On the other hand, the filter does almost nothing to the blue. In other words, it *transmits* the blue. A spectrophotometer is used to determine exactly how much of each color is absorbed or transmitted by various substances.

Taking Transmission Spectra

1. *Place filter number 821,* a red filter, in front of the entrance slit, as illustrated in Figure 10. The filter should be close to the slit, and *cover only the lower half* of the slit. Then you will be able to compare light which has passed through the filter with light which has not.

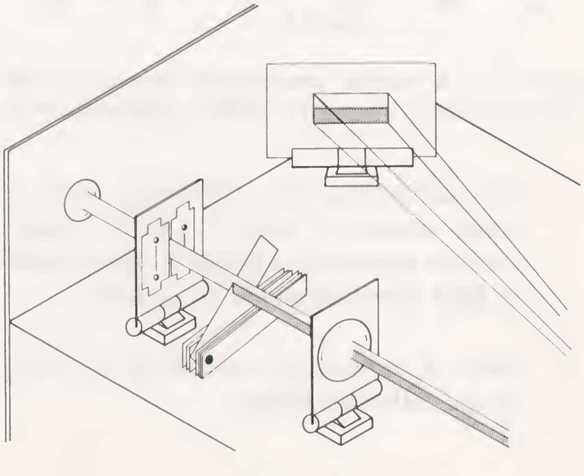


Figure 10.

2. *Estimate by eye the spectrum passed by the filter.* Judge the amount of light at each color using a scale with four values. You should be able to decide whether the light of each color coming through the filter is:

   *3–Very Bright–*As bright as with no filter. No light is absorbed by the filter.

   *2–Bright–*Most of the light gets through the filter. Some of the light is absorbed.

   *1–Dim–*Most of the light is stopped by the filter. Only some is transmitted.

   *0–Dark–*All of the light is stopped by the filter. None is transmitted.

3. *Record your results* on a graph like Figure 11.

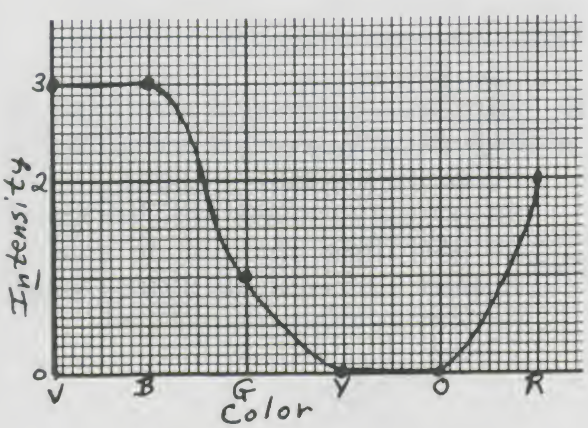


Figure 11. A sample transmission spectrum. The colors are violet, blue, green, yellow, orange, and red.

By connecting the dots you make a crude version of what is called a *transmission spectrum,* a graph of the amount of light transmitted for each color.

4. *Draw a transmission spectrum* for each of the following filters:

   Number 808, yellow

   Number 856, blue

   Number 871, green

   Number 880, gray

   The didymium filter

   Number 849, pale blue

5. *Repeat your measurements* for each filter, using double thicknesses. Either use two filter books or fold each filter over.

6. *Explore the transmission spectra* of some of the other filters. See if you can find the filter which produces the spectrum given in Figure 11. Also try combinations of filters.

SETTING UP A PRISM SPECTROPHOTOMETER

1. *Set up a different spectrophotometer using a prism* instead of a grating to break up the light. Use the same template but place the components as shown in Figure 12.

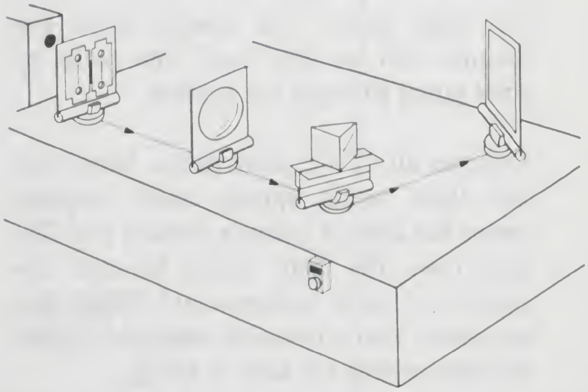


Figure 12. This spectrophotometer uses a prism to break up the light. It is similar in many respects to the grating spectrophotometer.

2. *Run through the Alignment Checklist* on page 10. To get the best spectrum, rotate the prism so that the spectrum is as far to the right on the card as it will go.

What differences do you notice between the spectrum made here by a prism and the spectrum made before by a grating? For convenience in comparing, the distance from the prism to the 3 X 5 index card has been made the same as the distance was from the grating to the 3 X 5 index card. Likewise, the distance from lens to prism equals the distance we had from lens to grating. Essentially, the grating has been replaced by a prism and no other changes have been made.

Using the Prism Spectrophotometer

1. *Repeat your experiment with the didymium filter* to get a better idea of the difference between the prism and grating. Estimate the transmission of each of the colors for the didymium filter. Graph the didymium transmission spectrum.

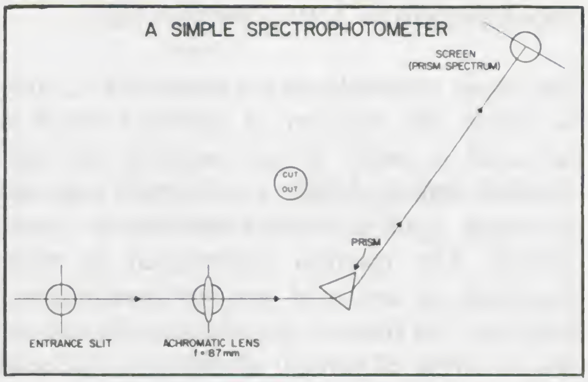


Figure 13. The layout showing the paths to use for the prism spectrophotometer.

2. *Compare the didymium spectra* taken by the grating and by the prism. What difference do you see? How do you account for it?

In Experiment B-3, you will compare in a more quantitative manner the spectra produced by a grating and a prism.

TRANSMISSION AND ABSORPTION

For many materials we are interested in, such as filters, the fraction of the light which is reflected is small. If one neglects the light which is reflected from a substance, then the incoming light is either absorbed or transmitted. The fraction transmitted is often expressed in terms of *percent transmission.* Likewise, the fraction absorbed can be expressed in terms of *percent absorption.* The sum of these two must be 100%. See Figure 14.

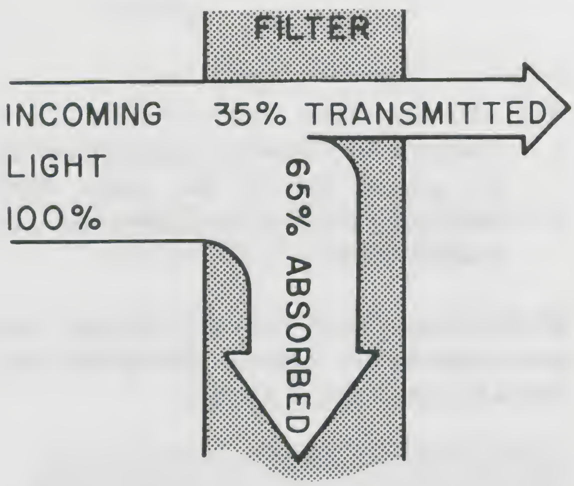


Figure 14.

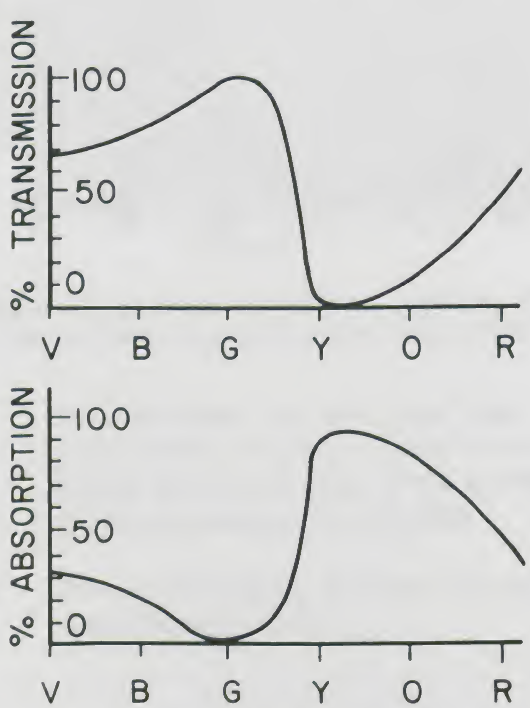


Figure 15.

The percent of incoming light transmitted depends on the color of the light. As you have seen, a red filter will transmit a large percentage of the red light falling on it. On the other hand, it will absorb large percentages of the colors which are far from red in the spectrum.

The graph of percent transmission for each color is called a transmission spectrum. The graph of percent absorption for the various colors is called an *absorption spectrum.*

These two graphs have an important relationship to each other. For each color the percentages of absorption and transmission add to 100%. Thus, where the transmission is large, the absorption must be small. There will be peaks on one graph where there are valleys on the other. See Figure 15.

Since these two graphs are so closely related, *either one can be used* to specify the light absorbing properties of a substance. The result of this is that some people use absorption spectra while others use transmission spectra. Likewise, some spectrophotometers read percent absorption while others read percent transmission. The important point to remember is that they are *equivalent measures* of the action of a substance on light passing through it.

ANALYSIS OF YOUR TRANSMISSION SPECTRUM

Now you should think about the transmission spectra you have. To direct your thinking about the measurements, use your spectra to answer the questions below. Place the letter of the correct answer in the space provided on the left.

___ 1. To the eye, the didymium and pale blue filters seem to be

   a. exactly the same
   b. quite similar but different
   c. quite different

___ 2. Judging by your spectra, these two filters seem to be

a. exactly the same
b. quite similar but different
c. quite different

___ 3. Which of the following colors was *absorbed* most by the didymium filter?

a. red
b. orange
c. yellow
d. green
e. blue

___ 4. What color was *absorbed* most by your *yellow* filter?

a. red
b. orange
c. yellow
d. green
e. blue

___ 5. Which of the following colors was *absorbed* most by the blue filter, number 856?

a. red
b. yellow
c. green
d. blue
e. violet

___ 6. From this information, what color do you guess can be removed from white light to make blue light?

a. red
b. yellow
c. green
d. blue
e. violet

___ 7. From the facts above, can you guess what color would be *transmitted* best by a yellow filter?

a. red
b. orange
c. yellow
d. green
e. blue

___ 8. Which color would be *transmitted* most by a green filter?

a. red
b. orange
c. yellow
d. green
e. blue

___ 9. Compared to the grating, the prism spreads the colors out more. True or False?

___ 10. Compared to the grating spectrum, the prism spectrum is brighter. True or False?

___ 11. The didymium spectrum transmitted by the grating is the same as that transmitted by the prism. True or False?

___ 12. A major difference between the grating and the prism is

a. none
b. the prism absorbs more light
c. the grating spreads out the colors more
d. the prism focuses the light better
e. the grating absorbs light of some wavelengths

___ 13. It is possible to find two filters that look alike and that would result in the same graph in this experiment. True or False?

Pretend you forgot to label your eight graphs. Can you figure out the color of each filter by looking at its graph? Try it.

What Happens with Two Filters?

Can you now predict the effect of combining two filters? For example, suppose each transmits 60% of the light of a particular color. The second filter "sees" only 60% of the incoming light. Therefore only 60% of this 60% gets through the second filter. Thus, 36% is transmitted by the two filters together.

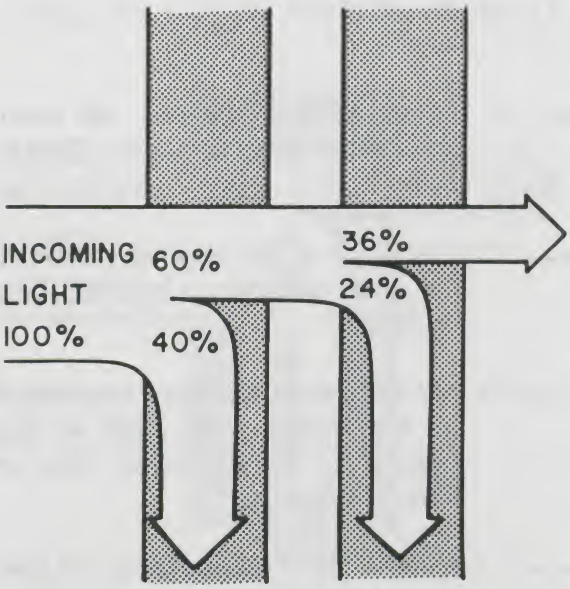


Figure 16.

In general, the fractions transmitted by each filter are multiplied together to obtain the net fraction transmitted. In this case the calculation was

$$t_1 \times t_2 = t$$

or

$$.60 \times .60 = .36$$

The fraction of light transmitted is therefore related to the *amount* of absorbing material. This relation is discussed further in Section C. It is the basis for the use of spectrophotometers in *quantitative analysis*—determining how much of a substance is present in a given sample.

Obtaining More Precise Results

If you can, compare your spectra with a friend's. You will probably find that you generally agree. Your spectra have roughly the same ups and downs as his. However, if you compare them carefully, you probably disagree with the exact position of some of the dots.

These disagreements are largely the fault of the light-detecting instrument—you. They would be expected even from the most careful experimenters. We need instruments that can measure light intensity with more accuracy than your eye.

You also need a more precise way of specifying colors. Red, orange, yellow, etc., are only general terms. Exactly where in the spectrum one color ends and the next begins can only be estimated. And the estimate will vary from person to person.

In the following pages we will describe color more precisely by introducing the term *wavelength* as a specification for color. In Section B we will show how color is related to our understanding of the wave nature of light. We will also extend the notion of wavelength to regions of the spectrum that our eye cannot see.

In Sections B and C of this module you will use these ideas to build a more accurate spectrophotometer. The spectrophotometer that you will build will be accurate enough for many useful laboratory measurements.

THE ELECTROMAGNETIC SPECTRUM

The Colors in Light

As you have seen, white light is a mixture of many colors. A prism or a diffraction grating is able to spread this mixture into its component colors to form what is called a spectrum.

Figures 17 and 18 show a diffraction grating

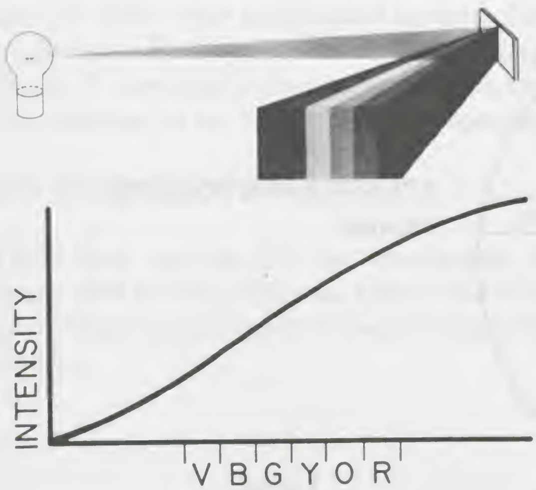


Figure 17. The emission spectrum of a "white light" lamp.

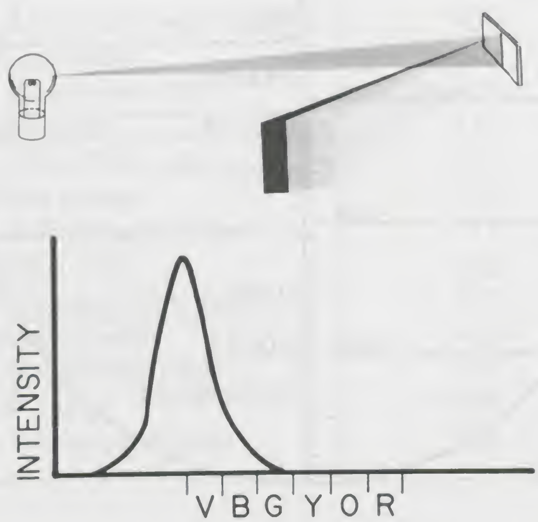


Figure 18. The emission spectrum of a "black light" lamp.

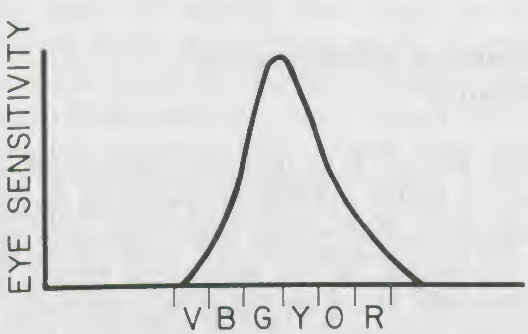


Figure 19. Relative sensitivity of the eye.

forming the different spectra produced by two different sources of light. *Emission spectra* show the intensity of the light a source emits for each color. Shown in Figure 19 is the *relative sensitivity* of the human eye; this shows that the eye is most sensitive to yellow light.

Note that the emission spectra extend beyond the red and violet ends of the spectrum. But the human-eye sensitivity does not. Your eye is not sensitive to light outside of the narrow range from what we call red to what we call violet.

The colors we see are visible only because certain molecules in the retinas of our eyes are sensitive to light in this range. When light strikes these molecules, they relay the information to our brains and we say the light is *visible.* If we had different sensitive molecules in our retinas, we might call light of some other range visible.

Electromagnetic Radiation

Visible light is only a small part of a vast range of radiation called *electromagnetic radiation.* This radiation includes radio waves, microwaves, x-rays, and gamma rays (see Figure 20). The radiation just below the red end of the spectrum is called *infrared,* which means "below the red." Similarly *ultraviolet* is the name for radiation "beyond the violet."

All electromagnetic radiation has essentially the same properties as light. For example, every type of electromagnetic radiation travels through a vacuum at the same speed, 300,000,000 meters per second (m/s). But each type interacts with matter differently, and it is these different interactions that technology exploits for various purposes.

Range of Spectrophotometers

Spectrophotometers are used for measurements in three regions of the electromagnetic spectrum: the infrared, the visible, and the

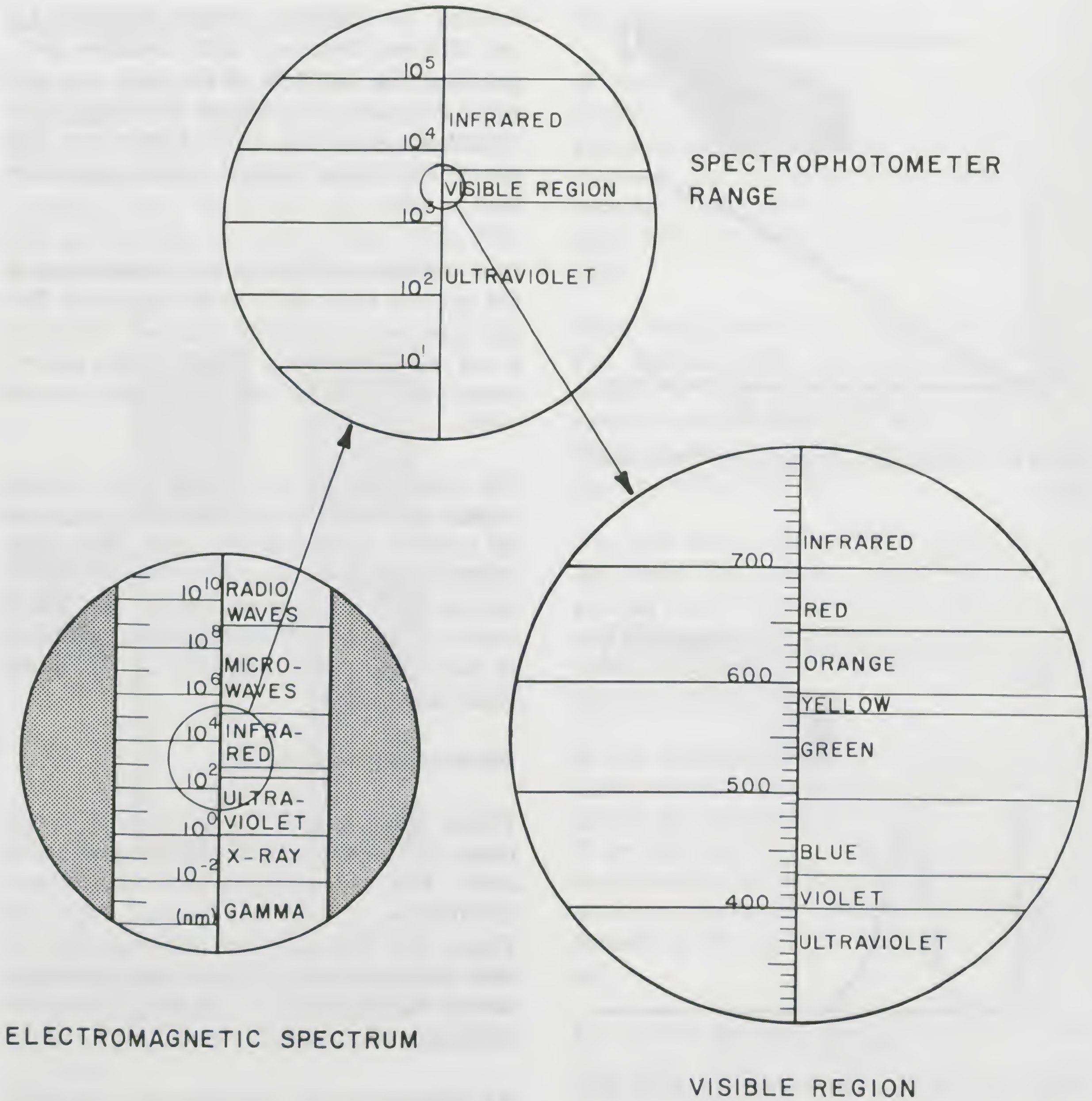


Figure 20. The electromagnetic spectrum, showing the range in which spectrophotometers are used for analysis and the region of visible radiation. The numbers given are the wavelengths in nanometers (10^{-9} m).

ultraviolet. Measurements in each of these regions present particular design problems, so that a single instrument rarely can cover more than one region without modifications.

The spectrophotometer that you are using is designed for the visible region. However, with suitable light sources and detectors, it can be used in the regions which are "close" to the visible region on either end. These regions are called the *near infrared* and *near ultraviolet.*

Wavelength Specification for Radiation

Since the eye is an imperfect instrument, we need a better method of specifying electromagnetic radiation than color. The term used is *wavelength.* In the visible light region, the wavelength of a given radiation is measured in *nanometers* (nan′-ō-me-ter), abbreviated nm. (1 nm is equal to 10^{-9} m.) The term wavelength derives from the wavelike character-

istics of light. This is discussed in some detail in Section B, but for the moment simply think of wavelengths as numbers which specify radiation in the electromagnetic spectrum.

The Wavelengths of Visible Light

Light that we can see has wavelengths between 400 nm and 700 nm. Table I shows the approximate wavelength of each of the visible colors.

Table I.

Color	Approximate Wavelength (nm)
Ultraviolet/violet edge	400
Violet center	410
Blue/violet edge	425
Blue center	470
Green/blue edge	491
Green center	520
Yellow/green edge	575
Yellow center	580
Orange/yellow edge	585
Orange center	616
Red/orange edge	647
Red center	690
Red/infrared edge	730

It is difficult to say exactly what wavelength each color is because the colors in the spectrum merge slowly from one to another. The table shows the accepted ranges of the colors of the spectrum, but it should not be taken too seriously. First, as you have seen, there is no sharp boundary between colors. Secondly, within each color range there are a number of *hues.* The information in Table I comes from the *Handbook of Chemistry and Physics* (Chemical Rubber Co.), and it is fairly arbitrary. Other handbooks give slightly different values.

It is also interesting to note how uneven the color widths are. In particular, note how narrow yellow is compared to green or red. Did you notice this in your laboratory observations?

The Wavelengths of *IR* and *UV*

Wavelengths are also assigned to the electromagnetic radiation that we cannot see. Radiation with wavelengths *greater* than the largest red wavelength is called *infrared (IR).* Radiation with wavelengths *less* than the smallest violet wavelength is called *ultraviolet (UV).* The chart below gives the approximate wavelengths for the *IR* and *UV* parts of the electromagnetic spectrum.

The wavelengths for each of these ranges that are close to the visible are often referred to as *near.* For example, wavelengths of about 730-5,000 nm are *near infrared.* Those wavelengths farther away are called *far.*

Radiation	Wavelength Range (nm)	
	near	far
Ultraviolet	385	1
Infrared	730	100,000

The *energy* carried by electromagnetic radiation depends on wavelength. The *greater* the wavelength, the *less* the energy. Thus, infrared radiation with large wavelengths has low energy. It is called *heat radiation* since it is emitted by any hot or even warm object. Ultraviolet radiation, on the other hand, has small wavelengths which means high energy. Ultraviolet is responsible for suntan and sunburn and it can cause eye damage if looked at directly. Therefore **be extremely careful with ultraviolet light sources.**

REVIEW

Summary

Light shining on a substance is either reflected, absorbed, or transmitted by it. A *spectrophotometer* is used to measure the amount of each color of light which is transmitted (or absorbed). Since each substance has a unique absorption pattern, spectrophotometer analysis can identify what substances are present in a sample.

The five major parts of all spectrophotometers are: a *light source* which produces light of many colors, and a *monochromator* which selects out one of the colors to pass to the *sample* to be analyzed. The amount of light transmitted strikes a *detector* whose output is amplified so that it can be registered on a *display* device.

The object of Experiment A-2 was to build a simple spectrophotometer using a diffraction grating to separate the light into a *spectrum,* and using your eyes as the detector. With this setup you could estimate the absorption patterns of various colored filters. From the data obtained you drew *transmission spectra.* You also repeated one of your measurements with a prism in place of the grating.

Transmission and *absorption spectra* for a sample are "mirror images" of each other. The light absorbed plus the light transmitted at each color must add to 100% of the incident light. Graphs of such spectra are the basis of *qualitative analysis,* determining what materials are present in a sample.

When the thickness of the sample is increased, the amount of light transmitted decreases. This is the basis for *quantitative analysis,* determining how much of each material is present.

Visible light is only a very small part of the *electromagnetic spectrum,* which includes radio waves, microwaves, x-rays, gamma rays, and infrared and ultraviolet radiation. Spectrophotometers are used for analysis in the visible, the near infrared, and the near ultraviolet portions of this spectrum.

A more accurate designation of radiation than color is *wavelength.* It is commonly expressed in *nanometers* (nm). The range of visible light is from about 385-730 nm, but it is impossible to assign exact numbers to visible colors since individuals perceive colors differently.

QUESTIONS

1. Which colors are left in light by the following filters?

   a. blue

   b. red

   c. both together

2. What is the color of the filter which would give each of the following transmission spectra?

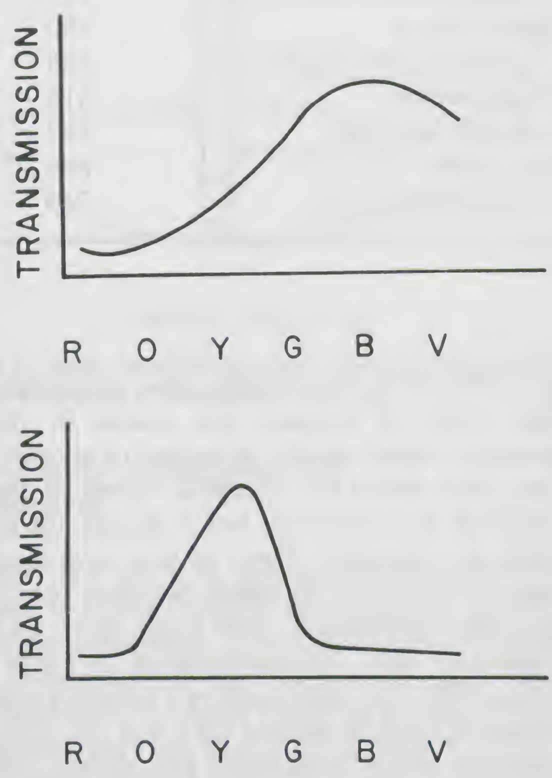


Figure 21. Top, A. Bottom, B.

3. Which of the following transmission spectra is that of a filter which stops infrared radiation?

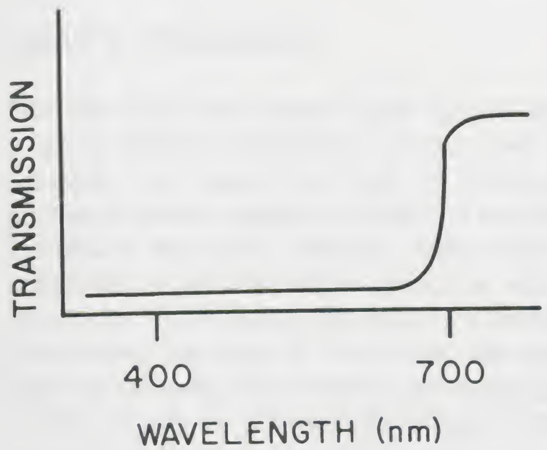


Figure 21C.

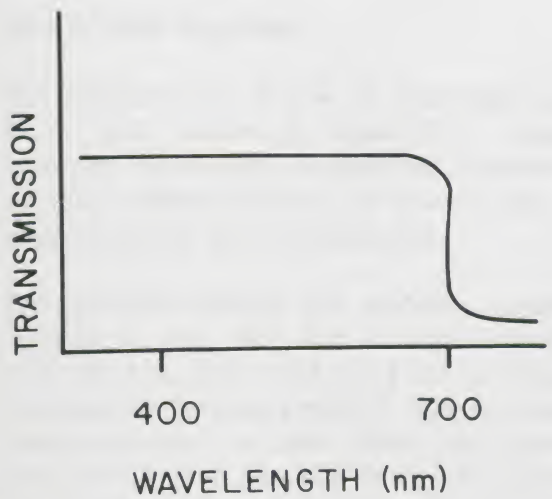


Figure 21D.

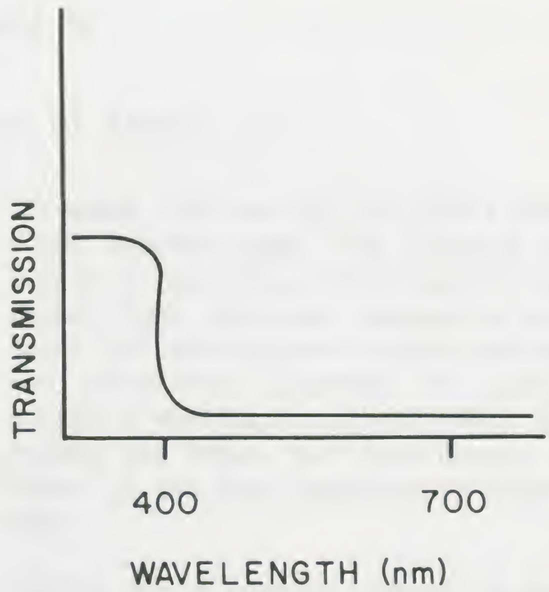


Figure 21E.

4. Which of the colors in the spectrum covers the largest range of wavelengths? Which covers the smallest wavelength range?

5. What are the five basic components in every spectrophotometer?

6. Describe each of the spectrophotometer components used in the first experiment.

7. Draw a diagram of the electromagnetic spectrum showing the wavelengths for the infrared, visible, and ultraviolet ranges.

SECTION B

The Dispersion of Light

WHAT IS DISPERSION?

The word *disperse* means "break up and cause to go in different directions." In the news, for example, you sometimes hear of police dispersing a crowd. Applied to light the word has essentially the same meaning. White light is composed of all the visible colors as well as ultraviolet and infrared radiation. In spectrophotometry we want to "break up" the white light (or separate it) by causing its component colors "to go in different directions." Then we can block out all the colors except the one we want to pass through the sample being analyzed.

How Is Light Dispersed?

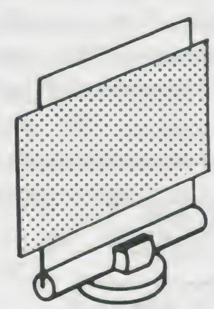
The problem then is how to break light up. When light strikes an object it is either reflected, transmitted, or absorbed. Therefore we must reflect, transmit, or absorb light in such a way that the colors separate.

The simplest solution has probably already occured to you. Why not use light absorption? That is, one could use a lot of filters, like those in the pack provided, each of which absorbs all but one color. Then you simply drop the filters in one at a time and measure the amount of light of each color that gets through the sample to obtain transmission spectra. While this solution is used in some instances, the problem is that filters which transmit only a single color, or a narrow band of colors, are expensive. And, to provide a filter for every wavelength would be quite expensive.

The Dispersive Elements

The other two solutions are by reflection and transmission. You have already seen that a *reflection type diffraction grating* can disperse the colors. You have also seen that a *prism,* which transmits light, also produces dispersion. In this section of the module we will explore these dispersive elements in some detail. You will see how the light reflection and transmission properties of materials depend on wavelength, and you will see how gratings and prisms have been cleverly designed to use these properties to disperse light.

Another type of dispersive element, the *transmission type diffraction grating,* is also provided with your laboratory apparatus. Its characteristics are essentially the same as those of the reflection type grating, and therefore they are not discussed in detail. However, you may want to observe its behavior.



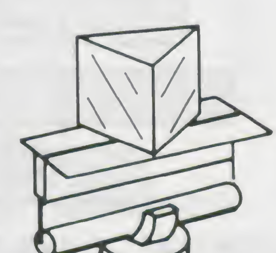


Figure 22. The two dispersive elements you will use in your experiment.

DISPERSIVE ELEMENTS

Prisms

A prism is a wedge of transparent material which "bends" light beams. For complicated reasons, violet light is more sharply bent by glass than is red light.

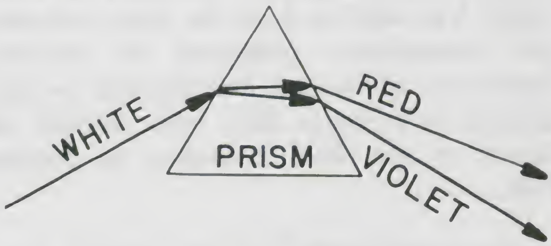


Figure 23.

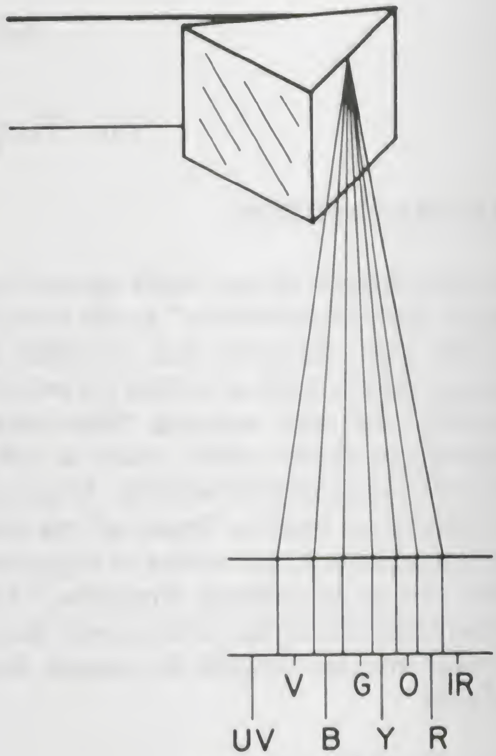


Figure 24.

A prism works best only for certain colors, leaving the rest still rather closely bunched together. For example, in Figure 24, violet is widely spread out while orange and red are quite compressed.

To surmount this problem, prisms for working in different parts of the spectrum are made of different materials. For example, prisms made of common table salt are used for the infrared part of the spectrum. Figure 25 shows the useful ranges of various prism materials. Note that the wavelength scale is *logarithmic,* so that a wide range of wavelengths can be conveniently covered.

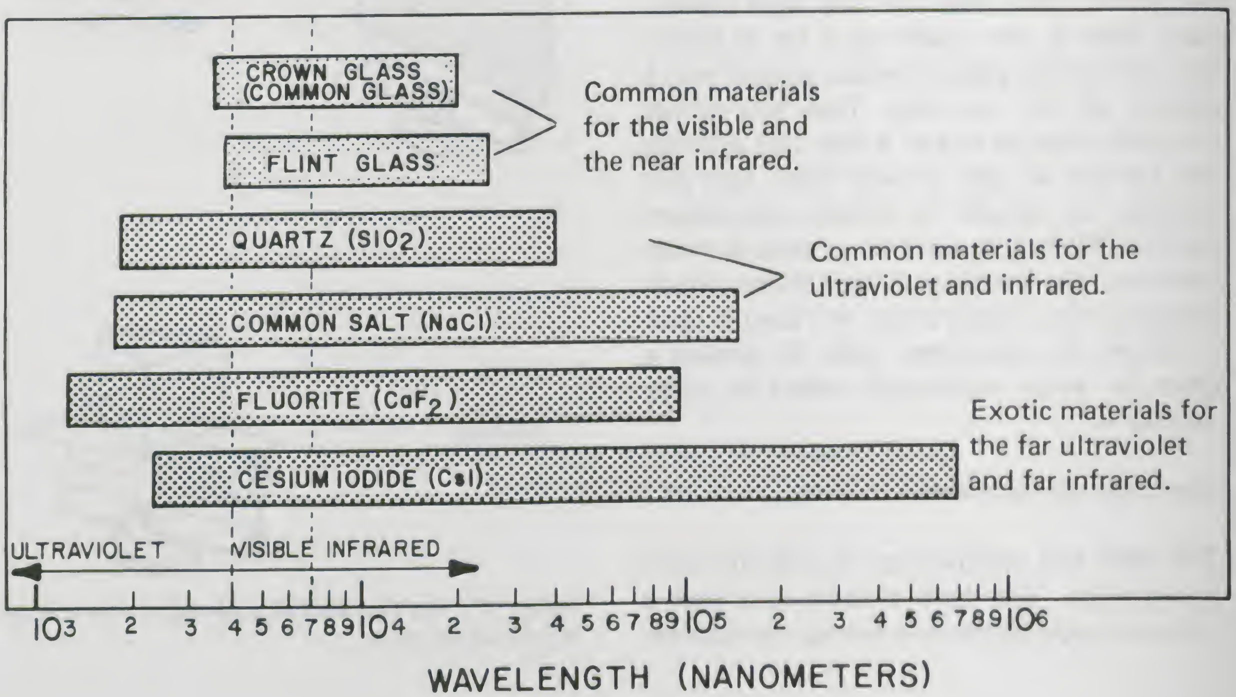


Figure 25.

Gratings

A reflection grating is a front-surface mirror with thousands of fine, parallel scratches on it. A grating reflects light in several ways:

Zeroth (0th) order: Simple white light reflection, like a mirror, with no dispersion. See Figure 26.

First (1st) order: On both sides of the zeroth order a bright spectrum appears. The spectrum on one side can be made much brighter than that on the other side by *blazing*.

Higher orders: Broader but weaker additional spectra appear. Sometimes these higher order spectra overlap.

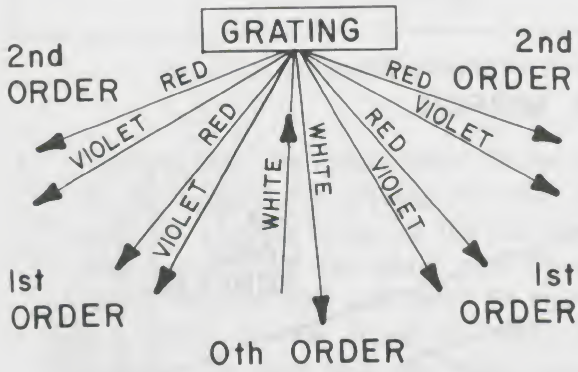


Figure 26.

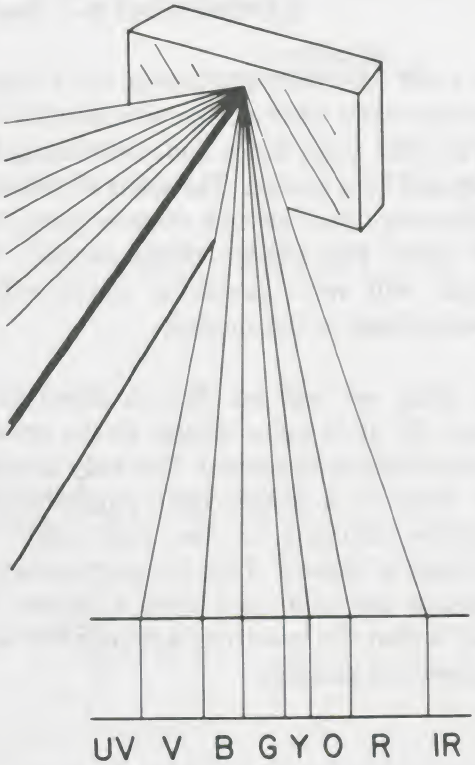


Figure 27.

The diffraction grating separates the colors much more evenly than does the prism, as Figure 27 indicates. However, the intensity of the light from the grating is less than that from the prism. The intensity is reduced because the incoming light is divided between simple reflection and spectra of several orders.

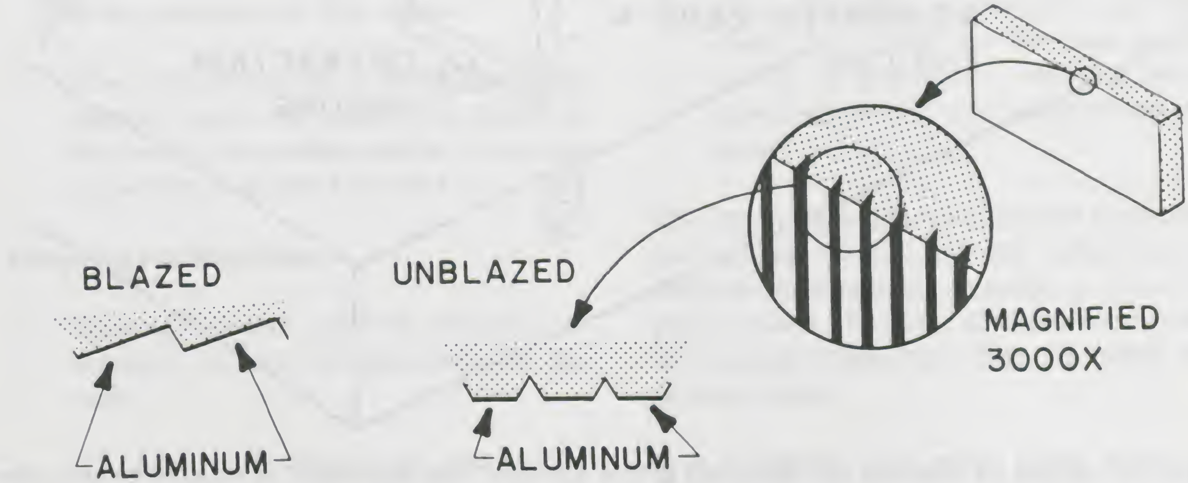


Figure 28. A magnified view of a reflection grating, showing the difference between blazed and unblazed gratings. The grating supplied has 13,400 lines per inch.

EXPERIMENT B-1. The Spectrum from a Diffraction Grating

The point of this investigation is to observe experimentally what a dispersive element does and in what ways this is done differently by a prism and by a grating. The spirit of this lab is exploratory: you should observe what happens when you change things around. This process will raise questions which will be answered later in this module.

The setup we will use first is illustrated in Figure 29. It is quite similar to the previous experimental arrangement. The only change is that there is a longer light path from the dispersive element to the card where the spectrum is viewed. This is accomplished by reflecting the light once from a mirror. The result is that the spectrum is fainter but larger and easier to measure.

Aligning the System

1. *Place the paper template* titled COMPARING A PRISM AND A GRATING securely on the base and centered on the center hole (see Figure 30).

2. *Attach the light-source box* and adjust the entrance slit, as in Section A, to get the maximum amount of light to pass through.

3. *Place the optical components* in the indicated positions. You may have to move your components somewhat around these positions to get the maximum amount of light squarely through each element.

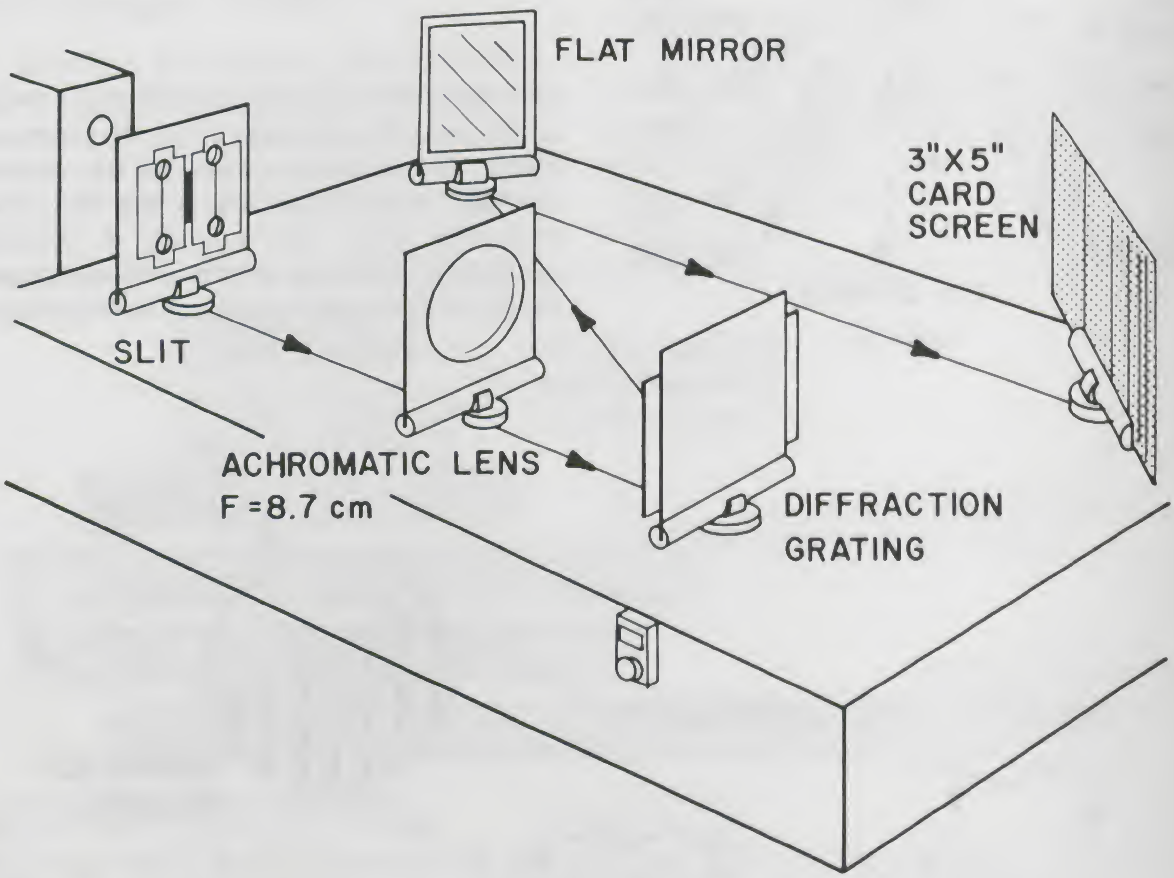


Figure 29. System for obtaining the diffraction grating spectrum. The light should be centered on each component both vertically and horizontally to maximize the intensity.

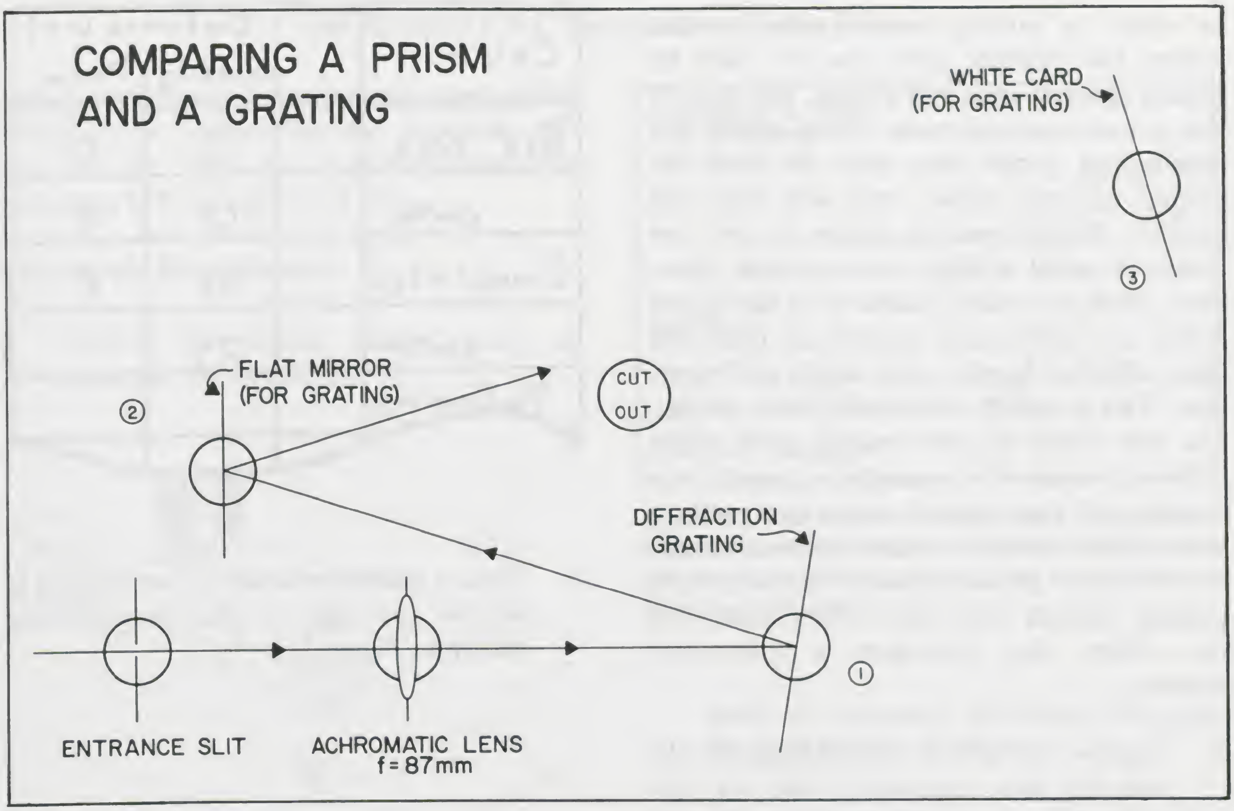


Figure 30. The layout showing the positions of components for the grating spectrum.

4. *Properly align the components.* To focus the lens turn the grating so that it provides a white image of the slit (the zeroth order) on the white card. Then move the lens back and forth to make the width of this image as small as possible. Be sure that the white light strikes each element (lens, mirror, etc.) at its center, both horizontally and vertically. This may require some tilting of the elements on their bases.

   When you think the system is properly aligned, check the system by following the beam with a white card or by putting some incense smoke into the box.

Observing the Spectrum

1. *Turn the grating* (without changing its position) to get the spectrum on the card.

   a. How many orders can you see on either side of the white image?

   b. Are the same orders on either side identical?

   c. How does the first-order spectrum compare to the second-order spectrum on the same side with regard to width and intensity?

   d. Do any orders overlap?

2. *Look carefully at the first-order spectrum.* The colors are the pure *spectral colors.* In particular, note the narrow pure yellow and the beautiful emerald green.

The spectrum is as interesting for what colors are missing as it is for the colors present. There is no brown, black, white, or any of the pastel colors like pink; all these are mixtures of spectral colors, and they are called *non-spectral* colors.

It is interesting that colors which *appear* the same to the eye, as some spectral colors, can

be made by mixing two or more spectral colors. For instance green can be made by mixing spectral blue and yellow, but there is also a pure spectral green. Other colors like brown and purple can *only* be made by mixing spectral colors (red and blue for purple). Mixing spectral colors to get new colors is called *additive* color mixing. However, when one mixes paints it is the colors which are subtracted (absorbed) from the light reflected by the paint which are important. This is called *subtractive* color mixing. The two kinds of color mixing yield rather different results. For example, a proper combination of the spectral colors can produce white light, whereas an analogous combination of paints produces black. Similarly, light passing through two color filters, one after the other, also undergoes a subtractive process.

3. *Explore the effects* of removing the slit and the lens, separately. Also try misalignment of each of the elements, sideways, and back and forth. Try this with incense smoke in the box so that you can see the effects more clearly. You should be able to determine the reasons for having these elements where they are.

4. *Return the elements to their proper positions and refocus* the system. Use the first-order spectrum for which red is at the right side of the card. Get the brightest possible spectrum centered on the white card.

5. *Adjust the white card* so that it is at right angles to the incident light.

Measuring the Spectrum

1. *Make a clear, neat table* of colors and color boundaries as shown in the sample. Use the designated space on the data page at the end of the module for your data table.

Color		Distance (mm)	
		Grating	Prism
Red edge		0	0
center		12	4
Orange edge		21	8
center		29	
Yellow edge			

2. *Place a millimeter scale* so that its zero is at the red edge of the spectrum (as shown in Figure 31).

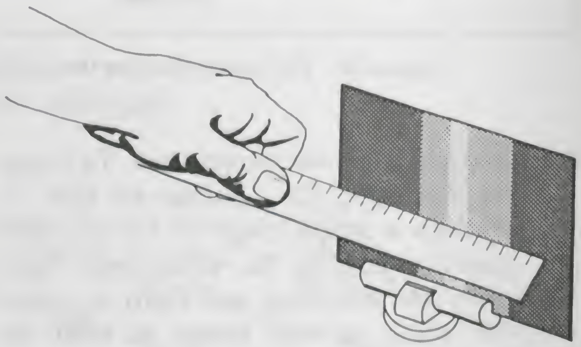


Figure 31.

3. *Record the location on the ruler* of the centers of each of the following colors: red, orange, yellow, green, blue, and violet. Even though it is difficult to do, try to estimate where the boundaries are between colors and record these also. Also record the location of the violet end of the spectrum. Your distances can only be estimates, using your eye. You will be surprised to see, later in the module, how well you have done.

EXPERIMENT B-2. The Spectrum from a Prism

This experiment is essentially the same as the previous one, except that the dispersive element to be used is a prism. Follow the procedure below to get your data.

Aligning the Prism System

1. *Replace the grating with a prism,* as shown in Figures 32 and 33.

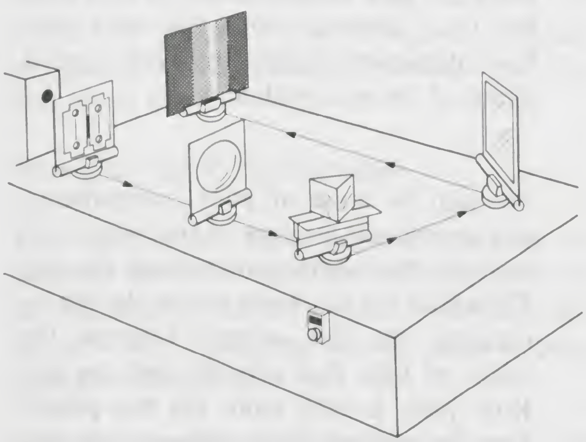


Figure 32.

2. *Align the system,* following the proper alignment procedure. **NOTE:** Do not move the lens or the slit. Adjust only the mirror at 3 and the card at 2.

3. *Rotate the prism* (without changing its position). What happens to the spectrum? As you turn the prism in one direction, you will see that the spectrum moves to the left, stops, then moves back. Adjust the prism until the red part of the spectrum reaches its maximum left position. This position is called the *angle of minimum deviation* and gives the least mixing of colors.

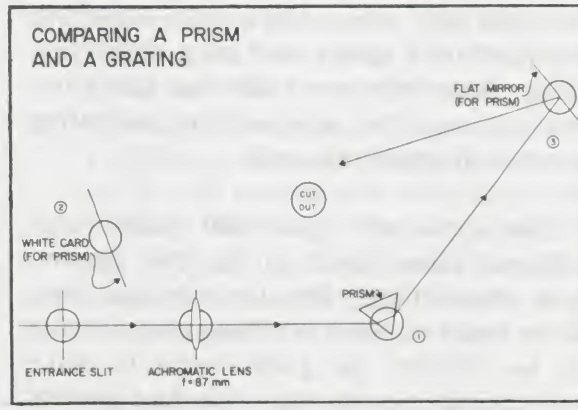


Figure 33. The layout of components. The distance from the dispersive element to the card is identical to the previous experiment, so that the two spectra can be compared exactly.

4. *Put incense smoke in the box* and observe the light paths. Note that, at the angle of minimum deviation, the angle the light makes with the side of the prism it enters is the same as the angle it makes with the side from which it exits.

5. *Adjust the white card* so that it is at right angles to the light striking it.

Measuring the Spectrum

1. *Place a millimeter scale* so that its zero is at the red edge of the prism spectrum, as you did for the grating spectrum.

2. *Measure the distances* to the color centers and boundaries as you did before, and record them in your table.

EXPERIMENT B-3. Comparing the Prism and Grating

You now have some data on the dispersive properties of a prism and of a diffraction grating. But there are additional characteristics that must be considered in comparing these two dispersive elements.

In this experiment you will make some additional observations of the two spectra. These observations, like the previous ones, will be based on your best judgment of what you see. Follow the guide below to make your comparisons of the prism and grating. Later we will explain the principles behind these observations.

Characteristics

Some of the characteristics that you can compare for the two elements are:

Brightness: Which element produces the brighter spectrum? That is, which spectrum has the higher intensity of light in each color? Why is it brighter? (Hint: How many spectra are produced by each element?)

Purity: Which of the elements produces colors which may be a slight mixture? Why do you think this happens?

Dispersion: Which element spreads out the colors more?

Uniformity: Which element spreads the colors out more uniformly, so that each band of color is more nearly the same width?

1. *Compare the spectra* obtained for the prism and for the grating. You may want to set one system up on your spectrophotometer and the other on your neighbor's. Or you might see if you can produce both at the same time on one setup. If you do the latter, be sure that the total distance along the light path from dispersive element to white card is identical for each system.

   To help in some of your comparisons, put an *exit slit* in place of the white card and put the white card behind the slit. Then scan the spectrum across the slit by rotating the flat mirror. Observe the beam of light that gets through the slit. How pure is each color for the prism? For the grating? What influence do you think the width of the slit makes on color purity? On intensity?

2. *Fill in the table* on the data page in the back of the module with your estimates of the brightness, purity, dispersion, and uniformity of the two elements.

EXPERIMENT B-4. Building a Better Spectrophotometer

As a final experiment in this section, you will assemble a good quality monochromator system using the diffraction grating. You will then add the light detector, amplifier, and display parts to make a complete spectrophotometer. This instrument will be comparable in quality to many commercial units.

Once your instrument has been constructed, you will use it to observe that there is indeed radiation "below the red" and "beyond the violet." In Section C you will use it to make an accurate transmission spectrum of the didymium filter.

Setting Up the Monochromator

The purpose of the monochromator is to disperse the white light from the source into its component colors in such a way that the operator can select any one of them to pass through the sample.

1. *Fasten the template* for the REFLECTION GRATING SPECTROPHOTOMETER to the monochromator table. Your instructor may prefer you to set up a different monochromator system. If so, he will provide you with the proper template. While this discussion describes the reflection grating monochromator, most of the steps apply also to other monochromator systems.

2. *Place the components* in their proper positions on the monochromator table. The mirrors (flat and spherical) are used to concentrate the pure colors on the exit slit. Have the white side of the exit slit facing inward. Each component can be *rotated* to direct the light to the next component and *tilted* to be sure the light travels parallel to the base.

3. *Properly align the mirrors.* One easy way

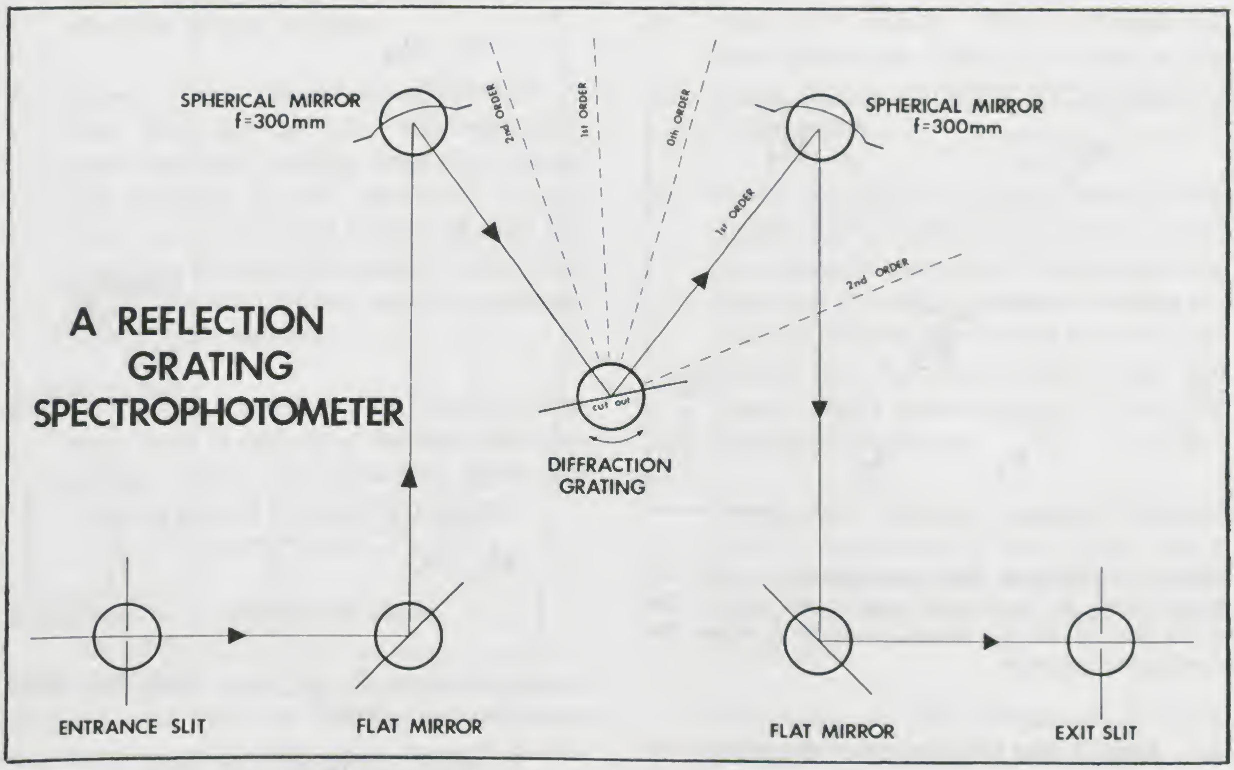


Figure 34. The layout of components for the reflection grating spectrophotometer. An illustration of this system is shown on the bottom of page 6.

to achieve the proper mirror alignment is to replace the diffraction grating with a flat mirror. Then the goal is to form an image of the entrance slit on the exit slit. When you have accomplished this and repositioned the grating, the optics should be in good alignment.

For aligning the components use a white card to trace the light path. Be sure the light beam is centered, both horizontally and vertically, at each step.

First, place the card in front of the spherical mirror M_2 (centered on the light-path line), and rotate and tilt M_1 until the light spot is centered on the card.

Next, place the card in front of M_3 and adjust spherical mirror M_2. Continue this process from component to component until an image of the entrance slit appears on the exit slit. Be sure each component remains near its designated spot.

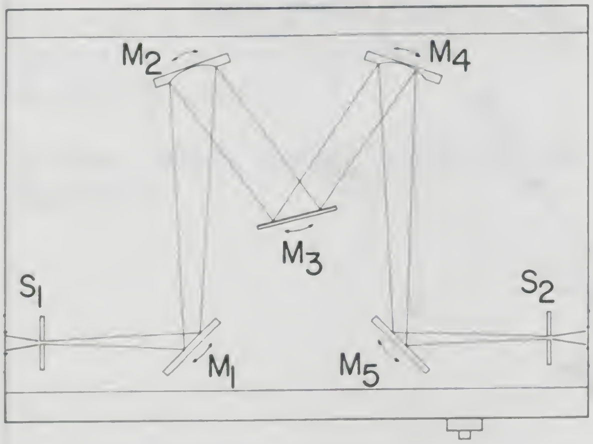


Figure 35. Aligning the monochromator. Slit S_1 should have its black side toward the source. The white side of slit S_2 should serve as a screen for viewing the spectrum.

4. *Make a fine adjustment* of the system by moving the exit slit back and forth until the smallest (and brightest) image appears on the exit slit. If the system is perfectly aligned, the image of the entrance slit should *exactly* match the size and shape of the exit slit, and all the light will pass through.

5. *Replace the mirror M_3 with the diffraction grating.* Rotate it so that the zeroth order (white light) falls on M_4 and produces an image of the entrance slit on the exit slit. If necessary, tilt the grating until the image is centered on the exit slit. Again, make a fine adjustment to produce the best image by moving S_2 back and forth.

6. *Rotate the grating counter-clockwise* until the first-order spectrum falls on the exit slit. As you scan the colors, be sure that each fully illuminates the exit slit.

7. *Close the monochromator box* and put

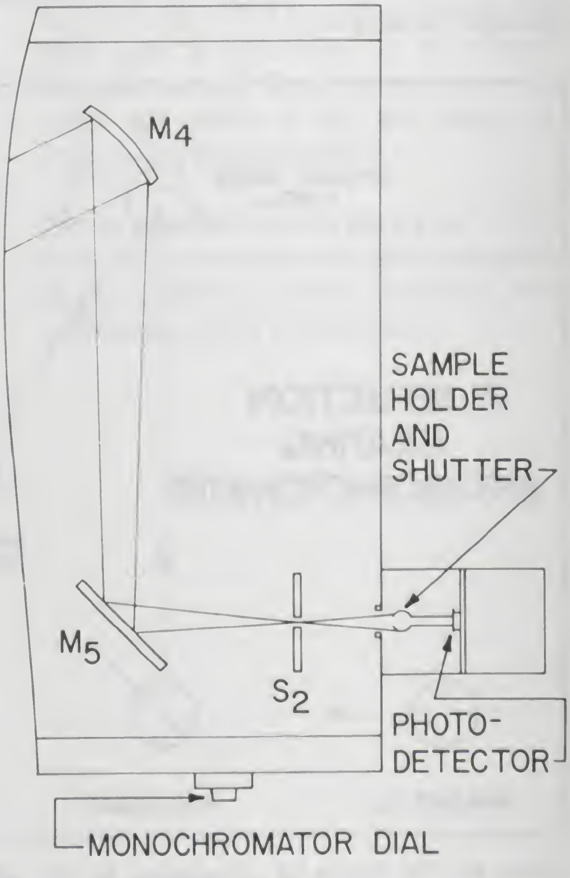


Figure 36.

smoke into the chamber. How well are your components aligned?

8. *Measure the spectrum* of this grating system as you did in Experiment B-2.

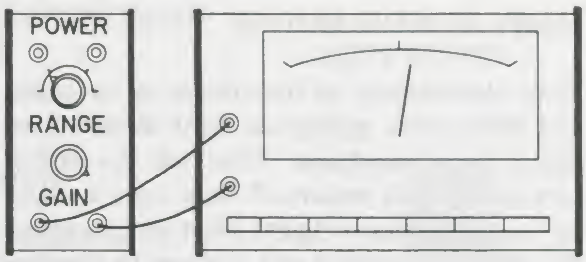


Figure 37.

Adding the Photodetector

Now that you have the optical components in the spectrophotometer, the next step is to add the photometer. Your strategy here is to get the maximum fraction of the light that comes through the exit slit to fall on the photodetector.

1. *Inspect the photometer box.* Observe the arrangement of the sample holder/shutter and photodetector. If your instructor permits, open the box to observe the parts more clearly.

2. *Attach the photodetector box* securely to the monochromator table at the hole the light comes through.

3. *Remove the sample holder/shutter* so that you can see the photodetector. Does the light coming from the exit slit fall squarely on the detector? If not, then you must *rotate* mirrors M_4 and M_5 together, changing the angle at which the beam hits the exit slit, until the detector is uniformly lighted.

4. *Replace the sample holder.* Rotate it and note how it acts as a shutter. With the shutter open, the detector inside the housing should be brightly lighted.

Adjusting the Amplifier and Meter

It is important that the electronics operate properly and that the system has sufficient wavelength range for your measurements. Your objective here is to test the amplifier and meter and to check the range of wavelengths over which the system will detect light.

1. *Plug the meter* into the terminals of the detector box marked METER, being careful not to bump the monochromator.

2. *Close the shutter, turn on the amplifier, put the RANGE SWITCH on 1000, and turn the GAIN all the way up (clockwise).* Put the meter on the 0.1-V scale. If the meter does not read zero, see your instructor.

3. *Open the shutter.* The needle should fully deflect to 100%. If it goes in the wrong direction, reverse the connections to the meter.

4. *Check the range of your system.* Use the digital dial on the front panel to rotate the turntable on which the grating rests. Scan the spectrum completely across the exit slit. The meter should stay fully deflected over the whole visible range. If it doesn't, have your instructor check the system out with you.

   Does your detector register radiation beyond both ends of the visible? Interrupt the light coming from the source to verify that this radiation is coming from the source.

   The *range* of your instrument is determined by the range of wavelengths over which your detection system will register 100% of full scale.

LIGHT AS WAVE MOTION

Your observations of the effects of the prism and diffraction grating on light should have raised some questions: What are the principles behind this behavior? How does it relate to the properties of light? What factors affect the ability of prisms and gratings to disperse light?

Before these questions can be answered, you must learn a bit more about light and its characteristics. One crucial point is that light acts in many ways like a "wave." In the following pages we discuss the wave properties of light and see how prisms and gratings use them to disperse light into its component colors.

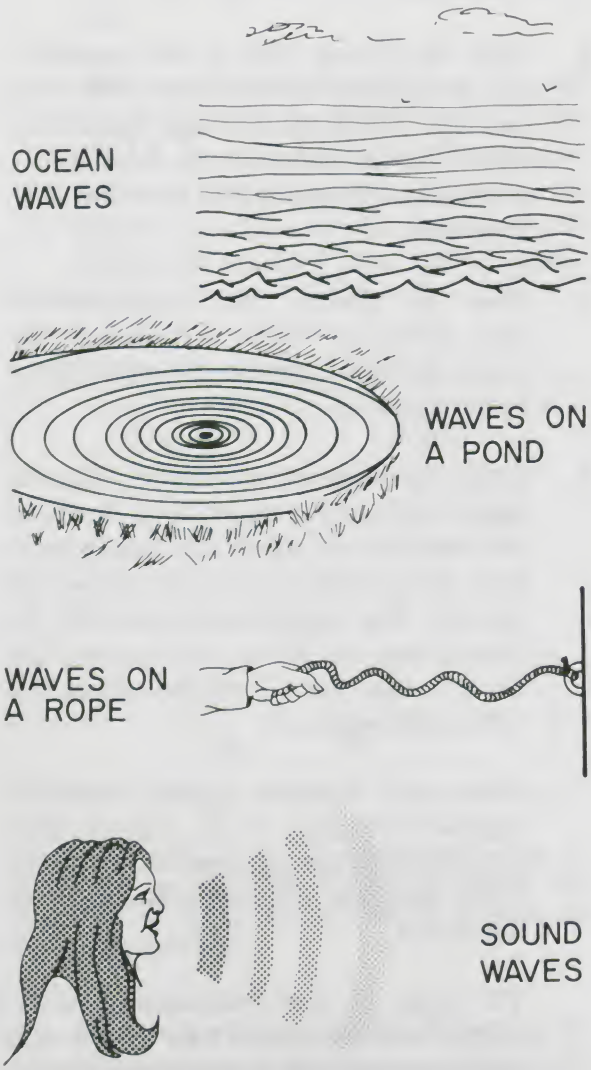


Figure 38.

What Is a Wave?

Ocean waves, ripples on a pond, a wave on a rope, sound, and light have one thing in common—they are all waves.

By a "wave" we mean a moving disturbance that produces an *oscillation* or vibration of some quantity as it passes. In ocean waves and ripples it is the height of the water which oscillates up and down; for waves on a rope, the position of the rope oscillates; for sound waves, the air pressure oscillates.

For light, the "electric and magnetic fields" oscillate. It is hard to visualize electric and magnetic fields, but if you were an electron, you would know all about them. Electric fields exert a force on electrons (and other electrically charged matter) that is just as real as the force an ocean wave exerts on a floating object. Whenever a light wave passes near an electron, it drives it up and down at a fantastic rate.

How Do We Know Light Is a Wave?

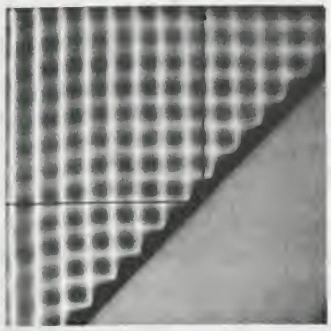
Since we cannot see the oscillating electric and magnetic fields of a light wave, nor can we directly see its effects on an electron, how can we say that light is a wave? The reason is that light behaves in many ways just like waves that we can see.

The illustration on the next page shows similar properties of light and of ripples in water. The light wave illustrations can be reproduced using your spectrophotometer apparatus. The water wave illustrations can be reproduced by a device called a *ripple tank.* This device is specifically designed to demonstrate the properties of waves. In the photographs the waves move in the directions of the arrows.

It is because of these similar properties that we say light is a wave.

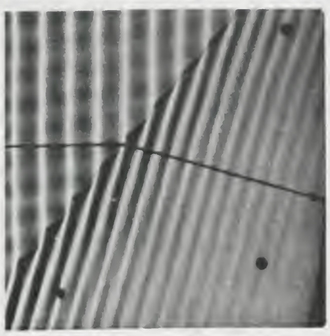
COMPARING THE PROPERTIES OF

WATER WAVES AND LIGHT WAVES



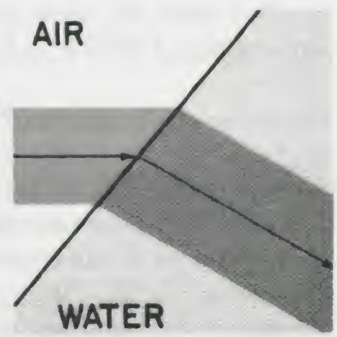
REFLECTION

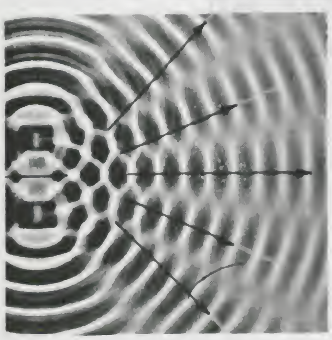
Reflection is the bouncing of waves off barriers. At the left, the waves cannot penetrate the block in the water. As a result, they bounce off in another direction. At the right a silvered mirror forms a similar barrier for the light.



REFRACTION

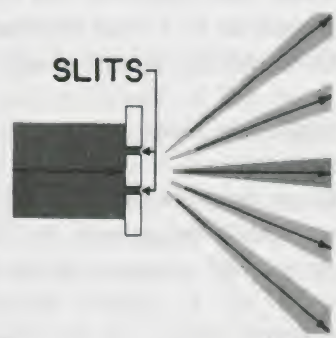
Refraction is the bending of waves when they change speed. In each illustration there are two regions in which the wave speeds are different. At the left the ripples travel from deep water to shallow water, where the speed is reduced. At the right, light enters water where its speed is about 75 percent of its speed in air.

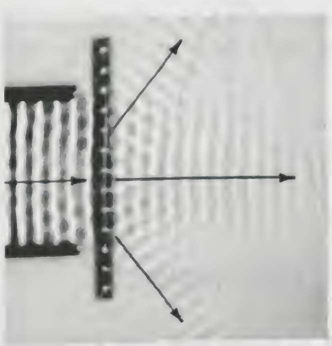




INTERFERENCE

Interference occurs when two waves interact. At left, water waves radiate from two arms bobbing at the same frequency. This gives regions of no water motion (destructive interference) separating regions where the waves are twice as high (constructive interference). Similarly two light sources of the same wavelength give alternating light and dark patterns.





DIFFRACTION

Diffraction is the bending of waves produced by obstructions. Here it is produced by regularly placed obstructions. At the left the obstructions are pegs in the water. These cause incoming waves to go off in particular directions. At the right, the pegs are replaced by thousands of regular scratches on a *transmission* grating. Similar beams result.

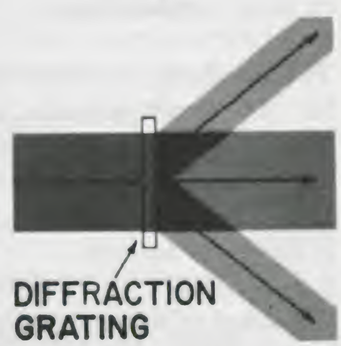


Figure 39.

Photos courtesy of Education Development Center, Inc., Newton, Mass.

HOW DO WE DESCRIBE A WAVE?

Three important quantities come up whenever we talk about a periodic wave: its *wavelength, speed,* and *frequency.*

Wavelength: A periodic wave is a sequence of regular, repeating cycles. The distance between identical points of two neighboring cycles is the *wavelength.* The Greek letter λ (*lambda*) is usually used for wavelength.

Speed: As time passes, the whole sequence moves. The distance moved divided by the time required is the wave *speed.* The symbol c is often used for wave speed. For light in a vacuum,

$$c \cong 3 \times 10^8 \text{ m/s}$$

Frequency: If you stand still as a wave moves past you and count the number of complete cycles that pass, the number per second is the *frequency.* It is often given the symbol f. Frequency is measured in cycles per second. This unit used to be abbreviated as cps, cycles, or s^{-1}. Now the units are called *Hertz* (Hz), which simply means cycles per second.

Light as a Wave

Since light exhibits wavelike properties, it is natural to measure it by its wavelength. Each pure color corresponds to an electromagnetic wave of a certain wavelength. Thus, the spectral colors can be classified and specified by their wavelengths.

The wavelength numbers we gave in Section A for the electromagnetic spectrum represent the wavelengths of the waves of the various types of radiation. For visible light this is extremely small, about 500 nm, or about 1/50,000 of an inch.

The speed of light waves, however, is extremely high, about 3×10^8 m/s, or 186,000 miles per second (mi/s). That is 7.5 times around

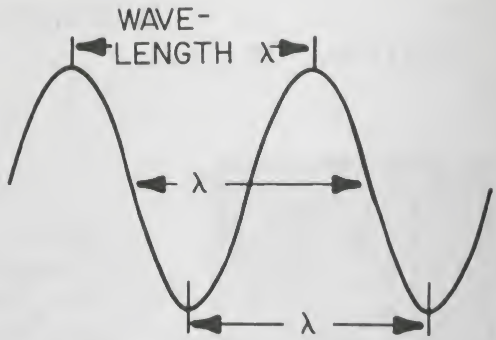


Figure 40. The distance between two adjacent crests is called *wavelength.* For light, each color is a different wavelength.

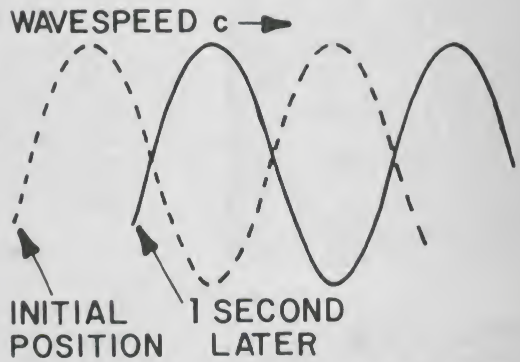


Figure 41. The distance a wave crest travels in one second is its *speed.*

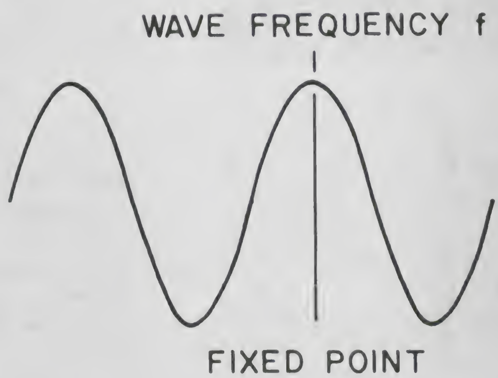


Figure 42. The number of crests that pass a point in one second is the *frequency.* For light, frequency (like wavelength) is different for different colors.

the earth in one second. This speed is the speed of light in a vacuum. It is slightly less than this in air, and much less in glass and most other transparent materials.

In a vacuum, light of all wavelengths has the same speed. But in transparent materials the speed is different for different wavelengths. The variation of speed with wavelength accounts for the dispersion by a prism.

Frequency can also be used to specify light colors. Wavelength is much easier to measure, so it is more often used. The frequency of light is around five hundred million million cycles per second (5×10^{14} Hz). At present, this is impossible to measure directly.

A Basic Wave Relationship

Wavelength, frequency, and velocity are not independent of each other. There is a basic wave relationship such that, if two are known, the third can be computed.

To get this relationship we need a new term, the *period* T. The period is the time in seconds for a complete cycle to pass a given point. Period and frequency are very simply related; they are reciprocals. That is, if the frequency is x cycles per second the period is $1/x$ seconds per cycle. Put mathematically,

$$T = \frac{1}{f}$$

For example, if the frequency is 10 Hz, then the period for each cycle is 1/10 s.

There is a simple relation between period, T, wavelength, λ, and speed, c. Recall that for any uniform motion:

$$Speed = \frac{\textit{distance}\text{ covered}}{\textit{time}\text{ required}}$$

A wave travels the *distance* of one complete cycle (the wavelength, λ) in the *time* for this cycle (the period, T). Since it is going at the *speed c,* then the basic speed formula gives:

$$c = \frac{\lambda}{T}$$

Now replace the period T with its substitute $1/f$ to get the basic *wave relationship:*

$$\lambda = \frac{c}{f}$$

This equation indicates that large frequencies correspond to small wavelengths.

WAVELENGTH SCALES FOR LIGHT

According to the wave relationship either wavelength *or* frequency can be used to specify light. For historic reasons, spectrophotometers generally use wavelength.

The Nanometer

Unfortunately, there are about a dozen wavelength scales in common use. For our work here, we will use the international standard (SI) unit. The SI unit of length is the meter and, since wavelength is a length, it should be measured in meters. But, since it is so small, it is generally measured in *nanometers. Nano* is the prefix for 10^{-9}. A nanometer (nm) is a tiny measure of distance equal to 10^{-9} m, or 10^{-7} cm.

Table II. Length Units

m = meter	
cm = centimeter	= 10^{-2} meter
mm = millimeter	= 10^{-3} meter
μ = micron	= 10^{-6} meter
nm = nanometer	= 10^{-9} meter
mμ = millimicron	= 10^{-9} meter
Å = Angstrom	= 10^{-10} meter

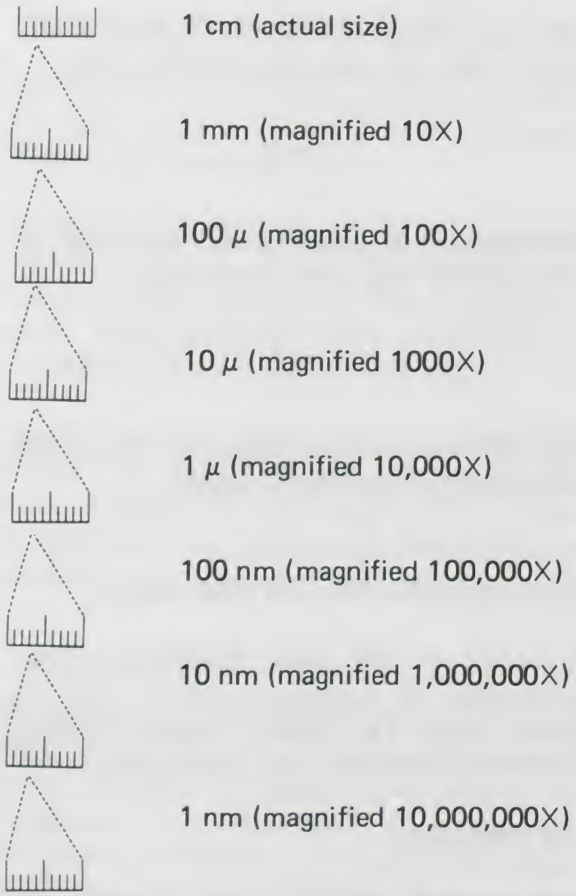


Figure 43.

Other Units

You will almost certainly encounter other wavelength units. The most common other unit used is the *Angstrom* (Å), which is one-tenth of a nanometer, or 10^{-10} m. You will also run across the unit *millimicron* (mμ) which is identical to a nanometer. It means one-thousandth (milli) of a micron, where a micron (μ) is 10^{-6} m.*

Wavelength Conversions

To convert wavelengths in one unit of length to wavelengths in other units, use the rules in the lists below. Since all of the wavelength scales are in decimal units, the conversions are relatively simple.

*Micron is short for micrometer, 10^{-6} m.

To convert a wavelength in other units *to* a wavelength in nanometers:

Multiply	By	To Get
meters	10^9	nanometers
centimeters	10^7	nanometers
microns	10^3	nanometers
millimicrons	1	nanometers
Angstroms	.1	nanometers

To convert *from* a wavelength in nanometers to a wavelength in other units:

Multiply	By	To Get
nanometers	10^{-9}	meters
nanometers	10^{-7}	centimeters
nanometers	10^{-3}	microns
nanometers	1	millimicrons
nanometers	10	Angstroms

THE FREQUENCY SCALE FOR LIGHT

In applications other than spectrophotometry, you may find light specified by its frequency. The frequency corresponding to a particular wavelength can be calculated using the wave relationship. For example, violet light is 400 nm. Its frequency is:

$$f = \frac{c}{\lambda}$$

$$= \frac{3 \times 10^8 \text{ m/s}}{400 \times 10^{-9} \text{ m}}$$

$$= 7.5 \times 10^{14} \text{ Hz}$$

Figure 44 gives the wavelengths and frequencies for some types of electromagnetic radiation.

With the use of this chart, conversions between the common wavelength units and frequency can be made quickly without calculations. The only drawback is that it has less than two-digit accuracy.

Note that wavelength increases from left to right while frequency increases from right to left. Do you know why? Also note that the scales are not linear; equal distances along the chart do not represent equal differences in wavelength.

To use the chart, locate the known quantity on one scale, then draw an imaginary vertical line at that location to the scale of the desired equivalent unit. A clear plastic ruler would be a great help in this.

For example, locate 7.5×10^{14} Hz. Tracing a vertical line upward shows that this is equivalent to violet light of 400 nm, as we calculated.

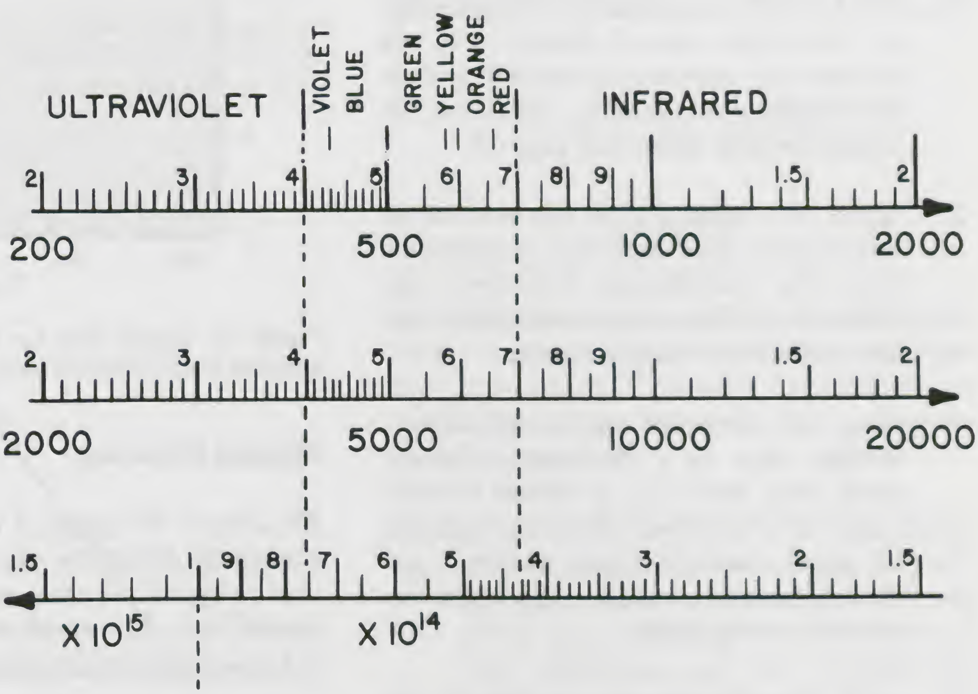


Figure 44. Wavelength-frequency conversion chart.

ANALYZING YOUR CURVES BY WAVELENGTHS

The data from your experiments can now be analyzed in terms of wavelengths. The central question is, what is the relation between the location in the spectrum of a color and its wavelength, for both the prism and the grating? Follow the procedure below to find this relation.

Graphing Your Data

The first step in analyzing your data is to graph it. You will graph the observed locations of each color on one axis and the wavelength of the color on the other. Hopefully, the resulting curves will reveal some simple relationship between location and color. An example is shown in Figure 45. The data are similar to yours, but the dispersive elements are different.

1. *Make a graph* like that shown in Figure 45. Lay out wavelengths at the bottom on an equally spaced (linear) scale. At the top, lay out the corresponding color boundaries and centers, as given in Figure 44 or in Table I on page 19.

2. *Graph the colors* against the position at which each color appeared, as measured from the red/infrared boundary. Put both sets of data on the same graph, but be sure to label which is which.

3. *Draw the curves* for each set of data. A straight edge or a draftsman's French curve may help you to obtain smooth curves. For the best curve, the number of points that are above the line (and their distances) should roughly equal the number that are below.

4. *Label the axes* and place a title on the graph to remind both yourself and others what the graph shows.

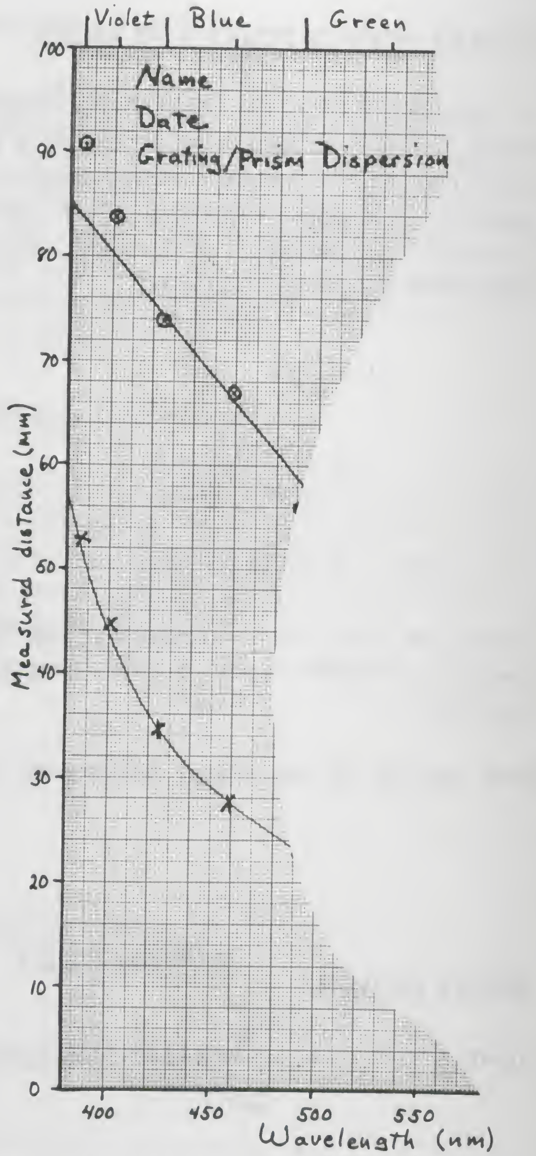


Figure 45. Typical data for two dispersive elements different from those you used.

Defining Dispersion

To analyze this graph it is necessary to more accurately define the word *dispersion.* Dispersion refers to the amount that the colors are spread out. *The more the colors are spread out, the greater the dispersion.*

Two facts about dispersion that relate to your graphs are:

1. *The dispersion is equal to the slope of your graph.* For a straight line graph, the slope is the vertical distance between two points on the line divided by the horizontal distance between the same two points. For your graph this will be a ratio of distance over wavelength. A steep slope means that slightly different wavelengths are found at quite different positions; this is what we mean by "spread out." A shallow slope means that different colors are found at nearly the same positions, not spread out. A horizontal line, with zero slope, means that the colors are all at the same position, and there is no dispersion at all.

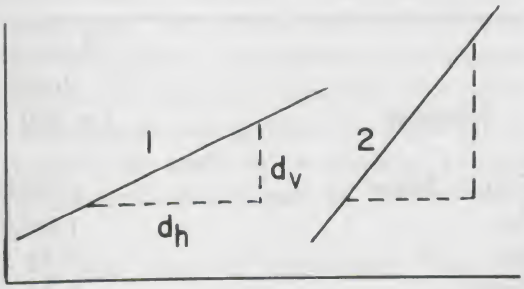


Figure 46. The slope of a straight line is the vertical distance between two points divided by the horizontal distance. Thus, slope = d_v/d_h. Line 2 has a greater slope than line 1.

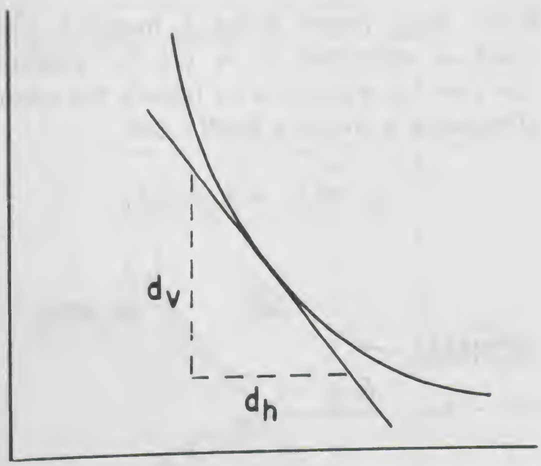


Figure 47. The slope of a curved line at a point is the same as the slope of a straight line which is tangent to the curve at that point.

2. *The dispersion can depend on wavelength.* If one of your graphs is a curved line, then its slope is changing. Therefore, the dispersion is changing. You can find the slope of a given point of a curve by drawing a straight line tangent to (touching at only one point) the curve, then the measured slope of the tangent line is the slope of the curve at that point. See Figure 47.

Calculating Dispersion

Since the slope of your curves can be determined you have a quantitative measure of dispersion. That is, the slope, and thus the dispersion, can be calculated in *millimeters per nanometer.* For example in Figure 45, the upper curve is a straight line. In the wavelength interval from 380 nm to 460 nm, the measured distance interval is from 85 mm to 66 mm. Therefore, the slope (and dispersion) is:

$$D = \frac{85 - 66 \text{ mm}}{380 - 460 \text{ nm}}$$

$$= .24 \frac{\text{mm}}{\text{nm}}$$

Note that *both* units in this ratio are *lengths.* Therefore you must be careful in your interpretation of *D.* It means the number of millimeters on the screen for each nanometer of light wavelength.

1. *Find the dispersion* of both the grating system and the prism system at wavelengths of 400 nm, 550 nm, and 700 nm. (First draw the tangent to the curve at that wavelength and then measure the slope of each tangent line.)

2. *Record your values* on the data page.

THE PHYSICS OF PRISMS

Refraction

The first question to ask about prisms is why the path of light bends or *refracts* when it enters glass. The answer lies in the fact that the speed of light is less in glass than in air. You can see this same effect in the following imaginary experiment. Imagine a line of marchers which has been given two orders:

1. March at full speed on the pavement but half speed on the grass

2. Always keep your shoulder touching that of the man on each side

Look at what happens when the line approaches the edge of the grass at an angle (Figure 48). In the second row, the first two players on the grass lag behind because they are marching more slowly. To obey order #2, they and the other soldiers must turn and march at a slightly different angle.

This illustration is only an analogy, but it does show what happens to light. For essentially the same reason, the light path bends when it enters at an angle* into a region in which it goes more slowly. This effect is called *refraction.* The amount of bending which occurs depends on the speed of light in the material; the slower the speed, the more pronounced the bending.

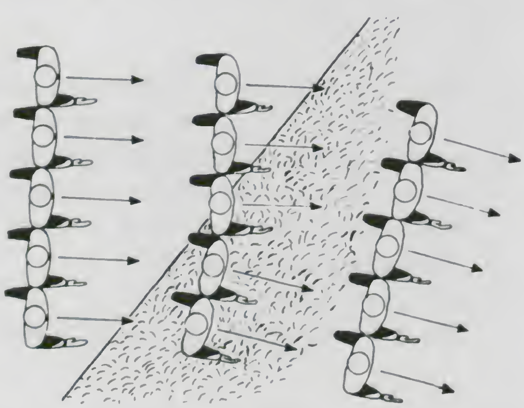


Figure 48. An analogy. Substitute light waves for the rows of marchers, and glass for grass, and you see why light paths bend.

Index of Refraction

The quantity which expresses the speed of light in a particular material is the *index of refraction, n.* This is the ratio of the speed of light in a vacuum, *c,* to the speed of light in the material, *v.*

$$n = \frac{c}{v}$$

Values of n for yellow light in common materials are given in Table III.

Table III.

Material	Refractive Index (at 589 nm)
Empty Space	1.0000
Air	1.0028
Ice	1.31
Water	1.33
Ethyl Alcohol	1.36
Plexiglas	1.49
Crown Glass	1.517

When light passes from a material whose index of refraction is n_1 (air for example), into one for which it is n_2 (glass), the amount of bending is given by *Snell's Law:*

$$n_1 \sin \theta_1 = n_2 \sin \theta_2$$

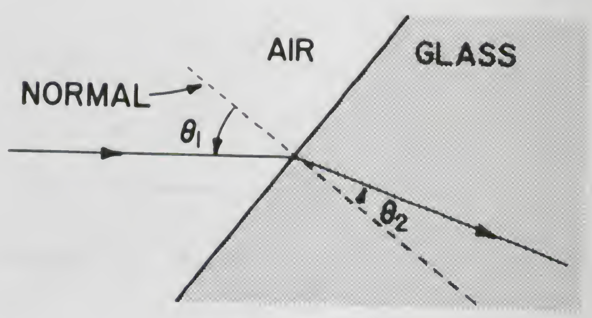


Figure 49.

*In refraction the angles are usually measured from the *normal,* a line which is perpendicular to the surface, to the light path.

For air, the index of refraction is very close to one, so that $n_1 = 1$ can usually be used. Then, for light passing from air into a material whose index of refraction is n_2, Snell's Law becomes:

$$\sin \theta_1 = n_2 \sin \theta_2$$

This expression can be used to determine the index of refraction of a material. One simply measures θ_1 and θ_2 for a light beam.

Index of Refraction and Wavelength

All of this does not explain the way a prism separates colors, however. The missing key is the following: *In a given material, the speed of light is different for different wavelengths.* Therefore the index of refraction depends on the wavelength—the greater the value of n_2, the smaller the angle θ_2. A smaller θ_2 means more of a bend. (See Figure 49.)

This is the basis of *dispersion.* Since the amount the light path bends depends on its speed, and since different wavelengths travel at different speeds, different wavelengths are bent by different amounts. This results in the colors dispersing to form a spectrum.

Figure 50 shows how the index of refraction changes with wavelength for various prism materials. Wavelengths for which the index of refraction is large are spread apart more. Compare the shape of the curve for flint glass with the dispersion curve for your prism over the visible wavelength range.

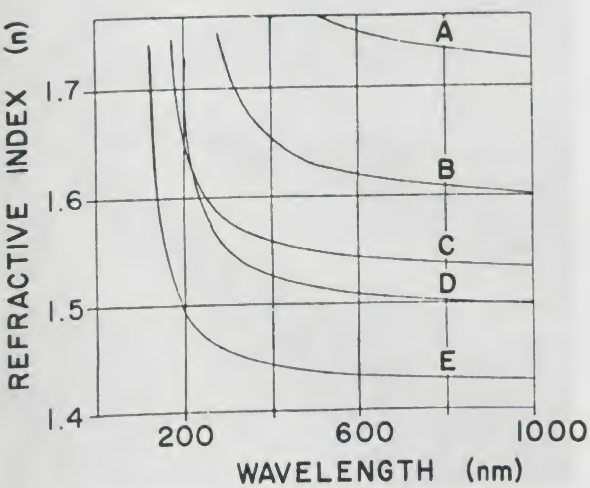


Figure 50. A is dense flint glass, B is light flint glass, C is crystal quartz, D is crown glass, and E is fluorite.

Dispersion by Prisms

You might ask why dispersion is not seen in flat window glass. According to our previous discussion, light bends toward the normal when it enters glass but away from the normal when it enters air. In flat glass, the light bends one way on entering and the *other* way on leaving. The emerging beam is slightly shifted but it is travelling in the same direction as the incoming beam. The dispersion that occurs in the glass is cancelled when the light re-enters the air. See Figure 51.

The design of the prism, however, is such as to produce a double bending of the light, and thus a greater separation of the colors. The 60°-60°-60° prism is the shape that is generally chosen for most spectrophotometer applications in the visible region.

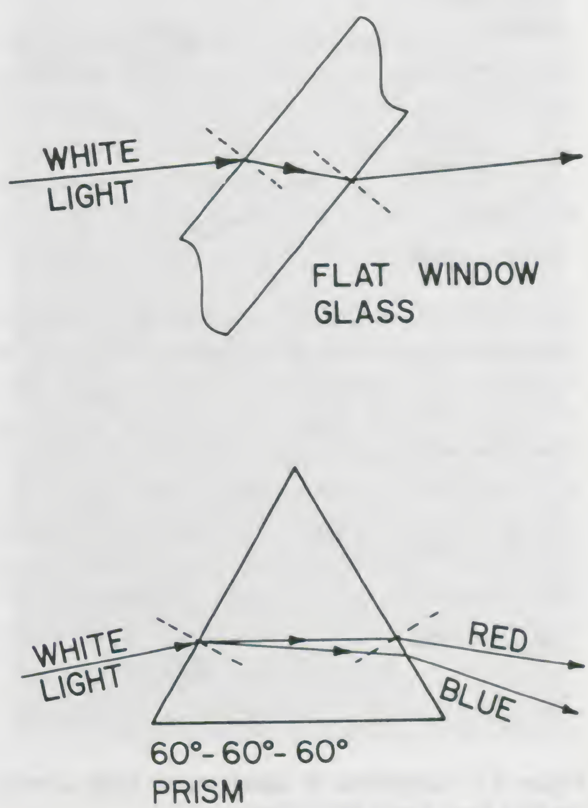


Figure 51.

THE PHYSICS OF GRATINGS

Diffraction

Gratings disperse light because of a peculiar property of waves. On page 35 you saw that, when a wave strikes a large flat surface, it reflects off in a different direction. However, when the size of the reflecting surface decreases to less than a wavelength, the reflection pattern changes. For example, Figure 52 shows what happens when parallel water waves strike a post whose width is much less than the wavelength. The incoming waves pass straight on, except where they hit the post. These waves are reflected off the post as *circular* waves, not simple parallel waves.

This property of waves is called *diffraction.* It occurs for all kinds of waves (water, light, sound, etc.) when they strike objects about the size of a wavelength or less. Thus Figure 52 also illustrates the diffraction pattern for a light wave striking a single thin strip of mirror.

When waves strike two such objects, two sets of circular waves are produced. These waves interact with each other, producing the vivid light and dark regions of Figure 53.

Look carefully at Figure 53. Assume that the black rings in the drawing mark the *crests* or high points of the waves, and the spaces between mark the *valleys* or low points. At the lighter regions of the drawing the black rings coming from the two mirrors lie on top of each other. Here the crest of a wave from one mirror adds to a crest from the other. This is called *constructive interference* and results in a stronger wave where the drawing is lighter.

On the other hand, the darker regions in the drawing occur when crests are added to valleys. There the waves cancel (*destructive interference*) and there is no wave (or light).

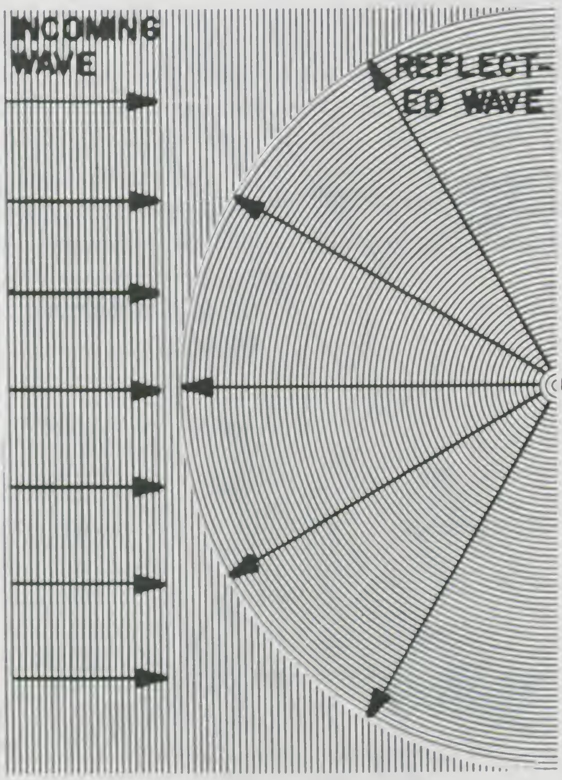


Figure 52. Reflection of water waves from a post (or light from a very thin mirror).

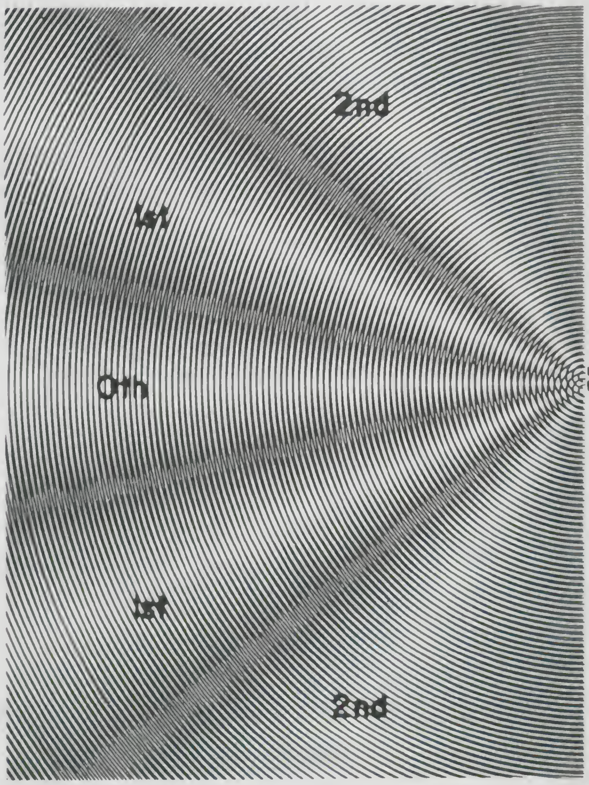


Figure 53. Reflection from two posts or mirrors. The incoming waves are omitted for clarity.

Diffraction Angle and Wavelength

To summarize, light reflected from two mirror strips produces several strong beams of light separated by regions of much less light. The beam reflected directly back is called the *zeroth-order* beam. On either side of the zeroth-order beam are symmetrically placed beams called *first order, second order,* and so on.

Look closely at the upper first-order beam in Figure 53. Pick a point in the middle of that beam where two rings overlap. If you count circles, you will see that this point is one ring, or one wavelength, farther from the lower mirror than it is from the upper one. This is true for every point in the first-order beam. A similar thing is true for the other beams, except that there is a difference of two wavelengths in the second-order beam, three wavelengths in the third-order, and so on.

This fact can be used to relate the angles of the strong beams to the wavelength of the incoming light. If one looks at a point P which is much farther from the mirrors than their separation, a, then the paths from the two mirrors are very nearly parallel, as shown in Figure 54. The extra distance, λ, travelled to P by the lower path is one side of a right triangle of angle θ. For this triangle:

$$\sin\theta = \frac{\lambda}{a} \qquad \text{1st order}$$

For higher-order beams, where m is the number of the order, similar reasoning shows the angle to be given by:

$$\sin\theta = \frac{m\lambda}{a} \qquad \text{mth order}$$

If one knows the mirror separation, a, one can use this relation to determine the wavelength of the light, λ, by measuring the diffraction angle, θ.

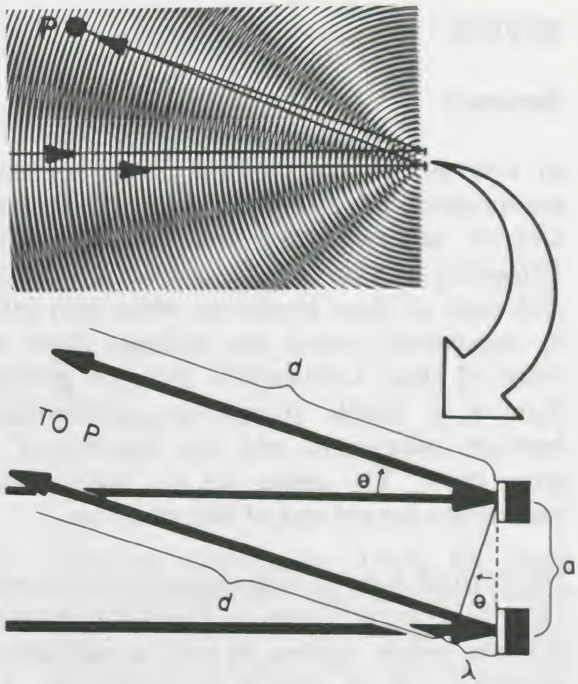


Figure 54.

Dispersion by Gratings

Diffraction gratings are essentially many parallel strip mirrors placed at equal distances from one another. The width of these mirrors is approximately that of visible light, a few hundered nanometers (see Problem #3). The pattern created is similar to that created by two mirrors.

Thus, the grating produces beams which obey the same equation as the beams produced by two strip mirrors. The key point, as applied to gratings, is that the *angle* of each order, θ, depends on λ. Therefore within each order *different wavelength light is diffracted at different angles.* This is the basis for *dispersion.* The longer the wavelength the greater the diffraction angle. Thus, red is diffracted through a larger angle than is violet, producing the spectrum you observed.

REVIEW

Summary

In this section you built a simple spectrophotometer and used it to study the characteristics of two *dispersive elements,* the diffraction grating and the prism. You found that each of them breaks up white light into its component colors and arranges these in order of their *wavelengths.* For the grating there is a simple straight-line relationship between wavelength and the location of a given color. The prism on the other hand compresses the red end of the spectrum.

You learned how to assign numbers to colors. These numbers are based on the fact that light acts like waves. Colors, as well as nonvisible radiation, can be named by wavelength, λ. The wavelengths of light are short, so special units of length, such as the *nanometer* and the *Angstrom,* are used. You learned the *wave relationship* $\lambda = c/f$, where c is the speed of light in a vacuum, 3×10^8 m/s, and f is the frequency of the wave. Light waves can also be specified by their frequencies.

The term which describes the ability of an element to separate white light into its component colors is *dispersion.* In prisms this results from the fact that light bends or is *refracted* when it enters a region in which it travels more slowly. The amount of bending is measured by the *index of refraction* n, which is the ratio of the speed of light in a vacuum, c, to that in the medium, v.

$$n = \frac{c}{v}$$

For most transparent materials the amount of bending depends on the wavelength of the light. When the materials are shaped into prisms, they can produce dispersion.

Gratings also disperse white light, but by a different mechanism. They are essentially a series of closely spaced mirrors. The reflected light of each mirror interferes with that from its neighbors in such a way as to send strong beams in certain directions. These beams are called *orders.* The angle that the mth order makes with the zeroth order (simple reflection) is given by:

$$\sin \theta = \frac{m\lambda}{a}$$

where a is the distance separating the mirrors. Since θ depends on the wavelength, light of different wavelengths comes off in different directions; in other words, the light is dispersed.

QUESTIONS

1. Is blue light bent less or more than red by a prism? By a grating? Why?

2. Does either the prism or the grating have approximately *constant* dispersion? (Look at your data.)

3. What property of a prism causes the spectrum it produces to be spread out differently for the red and blue parts of the spectrum?

4. Which dispersive element has the greater over-all dispersion?

5. For what regions of color are the dispersions of the prism and grating approximately equal?

6. Suppose that there were substances A, B, and C that had a speed-of-light versus wavelength dependence as shown in Figure 55. If prisms were made from each substance, how would they disperse the light?

7. What are the limits to the wavelength range of both prisms and gratings?

8. Describe why each of the important characteristics of light listed below is consistent with a wave picture for light.

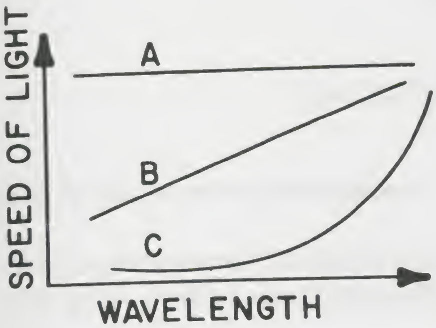


Figure 55.

a. reflection
b. refraction
c. interference
d. diffraction

PROBLEMS

1. Convert the following wavelengths to nanometers (nm):

   a. 3580 Å
   b. .64 μ
   c. 481 mμ
   d. 4.3×10^{-7} m
   e. 1.7×10^{-5} cm
   f. 358.41 nm

2. Convert 431 nm to:

   a. Å
   b. μ
   c. cm
   d. m
   e. mμ

3. Optional Experiment: Using the setup of Experiment B-1, measure θ for yellow light. Calculate a from the fact that the grating has 13,400 lines per inch. Then calculate the wavelength of yellow light. Careful measurements of this sort are a good way to determine wavelengths.

SECTION C

Spectrophotometer Analysis

How Good Is Your Spectrophotometer?

In the final experiment of Section B you put together a good quality spectrophotometer.

But how do you define "quality"? How do you specify "good"? And what effect did the other elements, slits, lenses, and mirrors have on both?

Here you will explore your system in detail to learn about some of these factors. Your analysis will be focused primarily on the characteristics of the monochromator since that is the emphasis of this module. But the behavior of the other spectrophotometer components, particularly the source and the light detector, is also important in determining the quality of the spectrophotometer.

These devices are treated in other modules of the Physics of Technology series, *The Incandescent Lamp* and *Photodetectors.*

What Is the Purpose of Each Element?

Because of effects we have so far ignored, prisms and gratings produce the purest spectra when illuminated with "parallel light." (If you divide the beam into a number of narrower beams, they will all be parallel, not diverging.) Therefore, most monochromators start by using a narrow slit and either a lens or a spherical mirror to make parallel light.

When the dispersed light leaves the dispersing element, a second lens or spherical mirror is used to focus the light at the entrance slit. Thus, at the exit slit, there are multiple images of the entrance slit, one for each color, but spread out into the spectrum. The exit slit is then placed so that only one color at a time comes through.

Figure 56 summarizes the components of spectrophotometers and emphasizes the purpose of each element in processing the light.

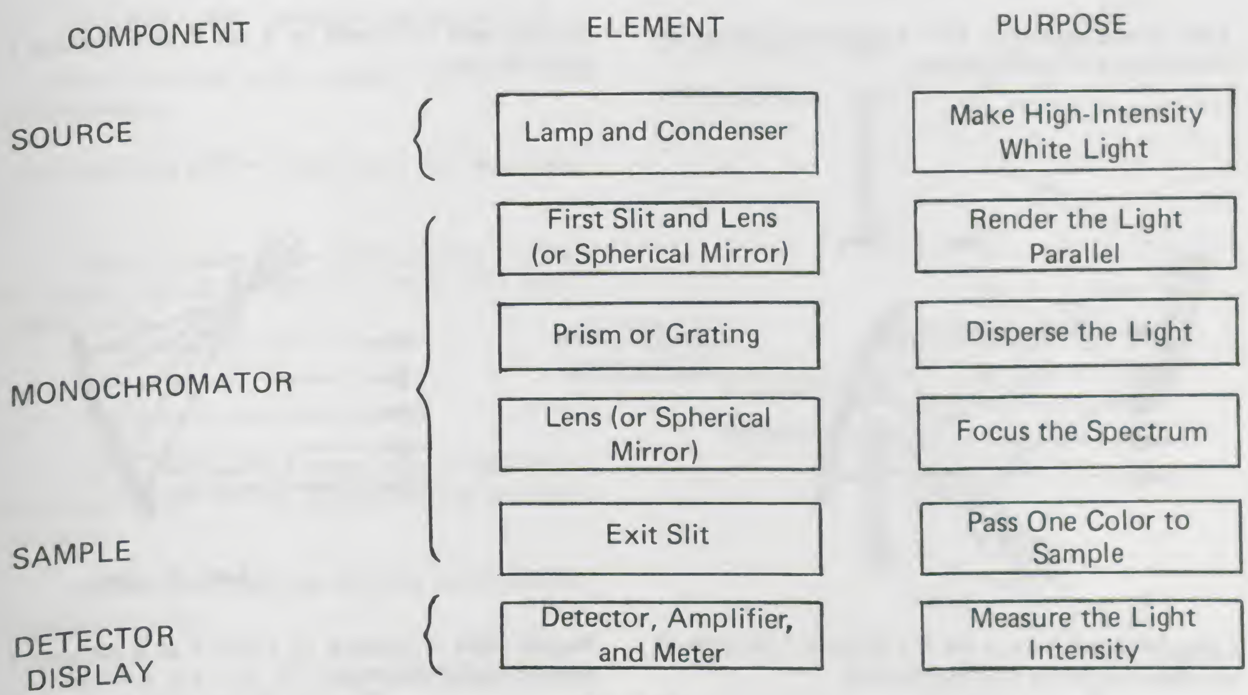


Figure 56.

Lenses and Spherical Mirrors

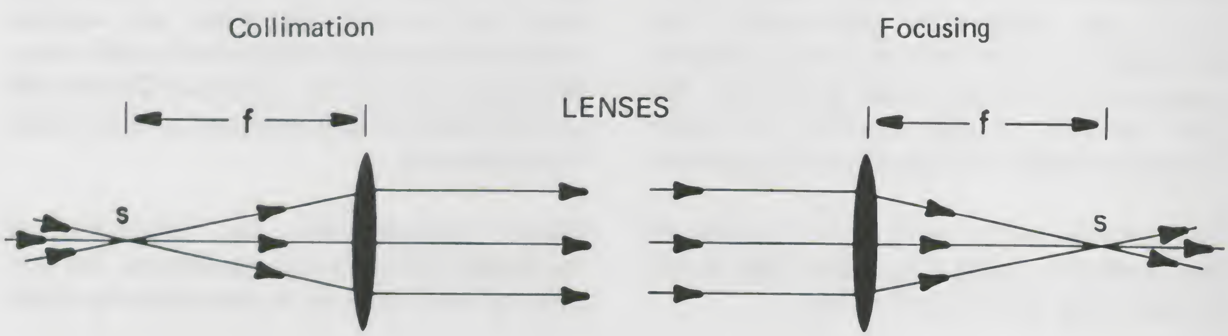
The block diagram on the previous page indicates that either a lens or a spherical mirror can be used to render the light parallel or to focus the spectrum. This is true because either lenses or spherical mirrors can perform the same two tasks:

Collimation: Collimating the light coming from the first slit simply means making the light beam parallel.

Focusing: Focusing the light coming from the grating or prism means forming images of the entrance slit on the exit slit.

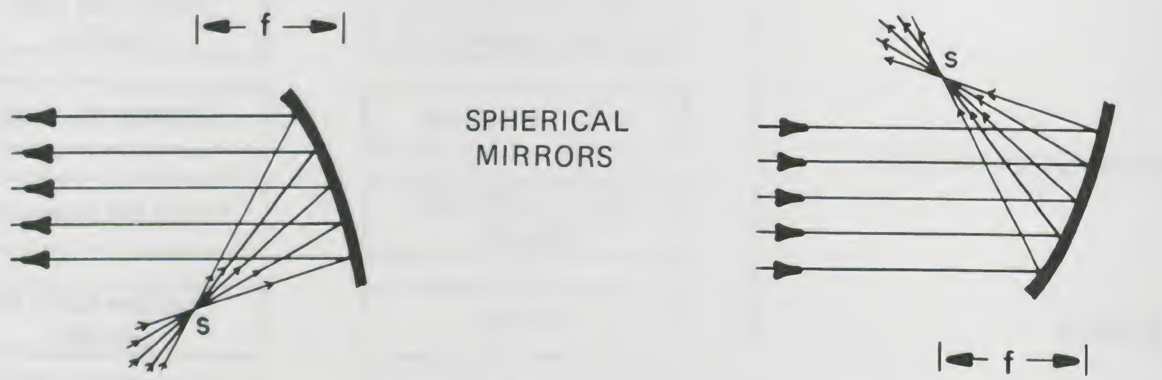
Figure 57 shows both a lens and a spherical mirror doing each task. The only difference between the two elements is that one uses *refraction* and the other uses *reflection.* In each illustration f represents the *focal length* of the lens or mirror and S represents the position of a slit. The focal length may be defined as the distance at which the slit must be placed in order to produce a parallel beam, or, conversely, the distance at which parallel light passing through a lens will come to a focus.

The figures on page 51 show how mirrors and lenses can be used in a monochromator system using a reflection type diffraction grating as the dispersive element. See if you can sketch a similar system using a prism as the dispersive element.



Light diverging from a slit S a distance f behind the lens emerges in parallel beams.

Parallel light is focused to a slit S at a distance f from the lens.



Light diverging from a slit S a distance f in front of the spherical mirror emerges parallel.

Parallel light is focused to a slit S at a distance f from the spherical mirror.

Figure 57.

A MONOCHROMATOR USING LENSES

The white light diverging from the first slit. . .

. . .strikes the first lens which *transmits* it as a parallel beam. . .

. . .so that it all strikes the grating at the same angle.

Different colors come off at different angles but all the light of a given color is in a parallel beam.

The second lens focuses these parallel beams of light to a point on the exit slit, different points for different colors.

The exit slit then lets only one color through, blocking the rest.

Moving the exit slit or rotating the grating would let a different color through.

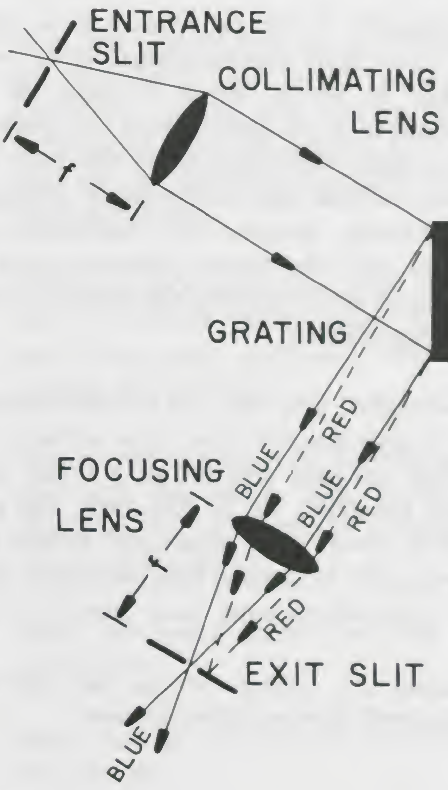


Figure 58.

A MONOCHROMATOR USING SPHERICAL MIRRORS

The white light diverging from the first slit. . .

. . .strikes the first mirror which *reflects* it in a parallel beam. . .

. . .so that it all strikes the grating at the same angle.

Different colors come off the grating at different angles, but all the light of a given color is in a parallel beam.

The second mirror focuses these parallel beams to a point on the exit slit, different points for different colors.

The exit slit then lets only one color through, blocking the rest.

Moving the exit slit or rotating the grating would let a different color through.

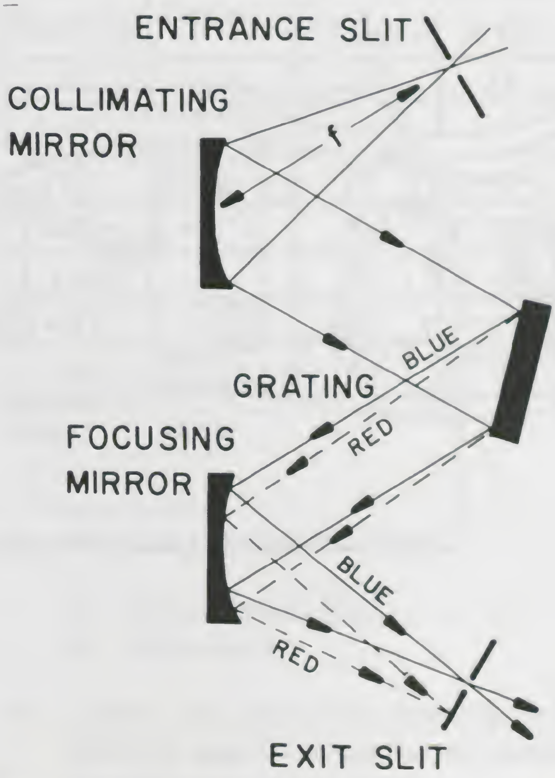


Figure 59.

EXPERIMENT C-1. Measuring Transmission Spectra

The objective of this experiment is to understand how well spectrophotometers work. One way to get at this is to build the best spectrophotometer system you can, then use it to measure the transmission spectrum of a substance whose light-transmission properties are accurately known. By comparing your spectrum with the known spectrum you will have a basis for evaluating the quality of your spectrophotometer.

The substance you will use for this measurement is *didymium.** You have already seen its effect on light and drawn a crude transmission spectrum for it. However, the spectrum has many more peaks and valleys than you were able to discern with your eye. These peaks and valleys have been carefully measured and are commonly used as a comparison standard for *calibrating* commercial spectrophotometers.

*Didymium is a mixture of the two rare earth elements neodymium and praseodymium.

This procedure will also serve a second purpose, that of calibrating your spectrophotometer. You have seen that colors can be accurately specified by their wavelengths. But how can you determine what wavelength is passing through the exit slit at any given time?

Your monochromator has been set up so that the grating sits on a turntable. By turning the digital dial on the front you can slowly turn the grating to scan the spectrum across the exit slit. Therefore all you need to do is to match the numbers on the dial with the wavelength passing through the slit. This process is called *calibration*, and it can be carried out with your didymium spectrum.

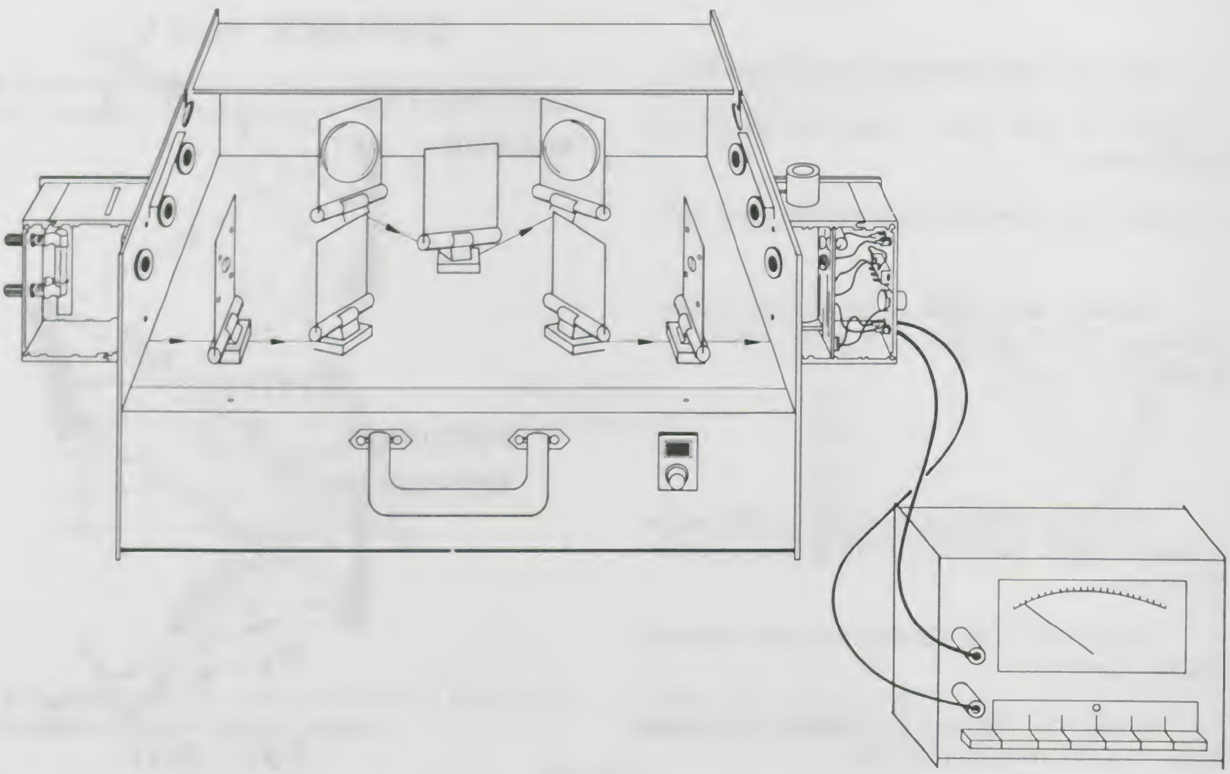


Figure 60.

Setting Up the Spectrophotometer

1. *Set up the REFLECTION GRATING SPECTROPHOTOMETER* of Experiment B-4. Refer to the procedures of Experiment A-1 for **Setting Up the Light Source** and the procedures of Experiment B-4 for **Setting Up the Monochromator, Adding the Photodetector,** and **Adjusting the Amplifier and Meter.**

2. *Measure and record on the data page the widths of the entrance and exit slits.*

3. *Measure and record the width of the image of the entrance slit* on the exit slit. To do this rotate the grating so that the zeroth order is focused on the exit slit and measure its total width. If your grating is of excellent quality, this will be exactly the same width as the entrance and exit slit. For a poorer quality grating, the image will be wider and may have fuzzy edges.

4. *Set the monochromator dial to read 000.*

5. *Rotate the grating by hand* so that the first-order spectrum which has the violet on the right is displayed on the exit slit and the ultraviolet-violet edge is about 0.25 in to the left of the slit (Figure 61).

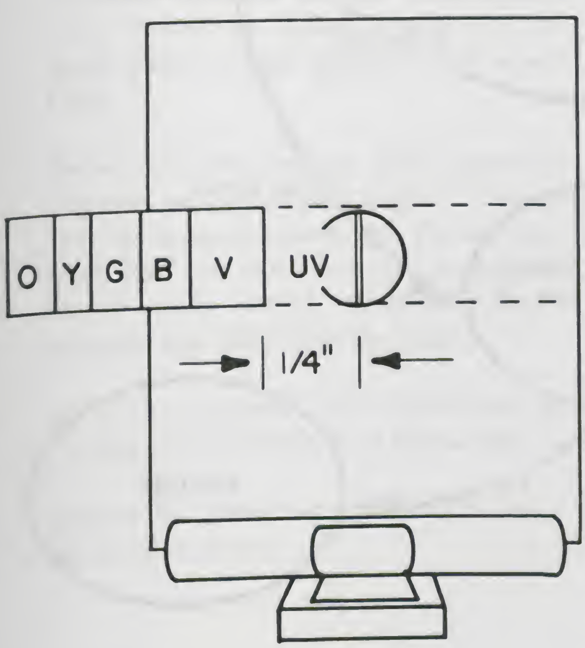


Figure 61.

6. *Turn the dial* to scan the spectrum past the slit. Go at least to the red-infrared boundary. If the dial reaches the end before this, turn the grating by hand so that the red-infrared boundary is to the right of the slit.

   Your meter should stay fully deflected over the whole visible range. If it does not, have your instructor check your system out with you.

7. *Return the spectrum* to its original position with the dial, so that the dial reads 000 and the spectrum is positioned as shown in Figure 61.

8. *Place the metal cover over the monochromator.*

9. *Make a data table* on the data page like that below.

Dial Reading	Color	% Transmission	
		Didymium	#849
0	None	57	77
500	Blue Edge	82	56
550		85	57
600		88	58
650		89	~~[illegible]~~ 54
700	Blue Center	88	51

10. *Find the following two filters:*

    A. The didymium filter
    B. Filter #849

11. *Follow the steps in the flow diagram* on the next page to obtain the transmission spectra for these two filters.

MEASURING A FILTER SPECTRUM

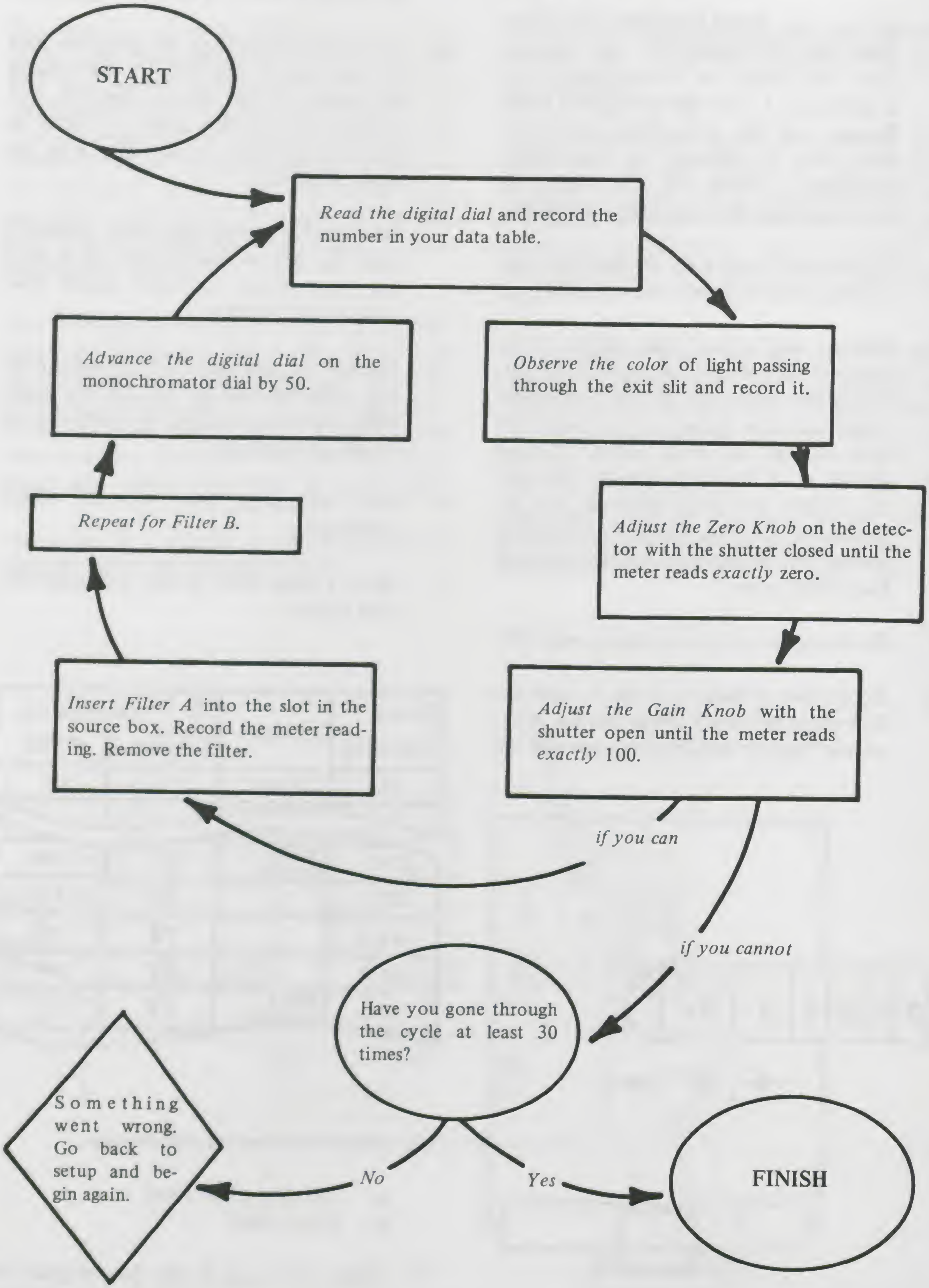


Figure 62.

ANALYZING YOUR DATA

Drawing the Transmission Spectrum

The numbers recorded for the filters are the percent of light transmitted at each different color. The way we adjusted the meter if no light was absorbed, the meter read 100, meaning 100% was transmitted. Similarly, if the meter read zero, it was the same as totally blocking the light with the shutter, indicating that zero percent was transmitted. If the meter read 50, half the light was absorbed, half transmitted.

You can now look at the numbers in your table and see that while the two filters may look similar to the eye, they are not the same. This means that the spectrophotometer has measured *quantitative* differences between the two. A graph of the data will make these differences even more apparent.

1. *Label a piece of graph paper* with *Dial Reading* on the horizontal axis and *Percent Transmission* on the vertical axis, as illustrated in Figure 63.

2. *Plot your data* for the two filters on the same piece of graph paper. To distinguish between the two sets of data use different symbols for the data points (e.g., ⊙ and x). Label clearly on the graph paper which symbol is for which filter.

3. *Draw the best smooth curve* you can through each set of data points to obtain your transmission spectrum. *Do not* connect the dots with straight lines. This would imply abrupt changes in transmission, and that is not the case.

4. *Label the observed color boundaries* on the top of your graph as in Figure 63.

5. *Answer the following questions* by looking at your graph.

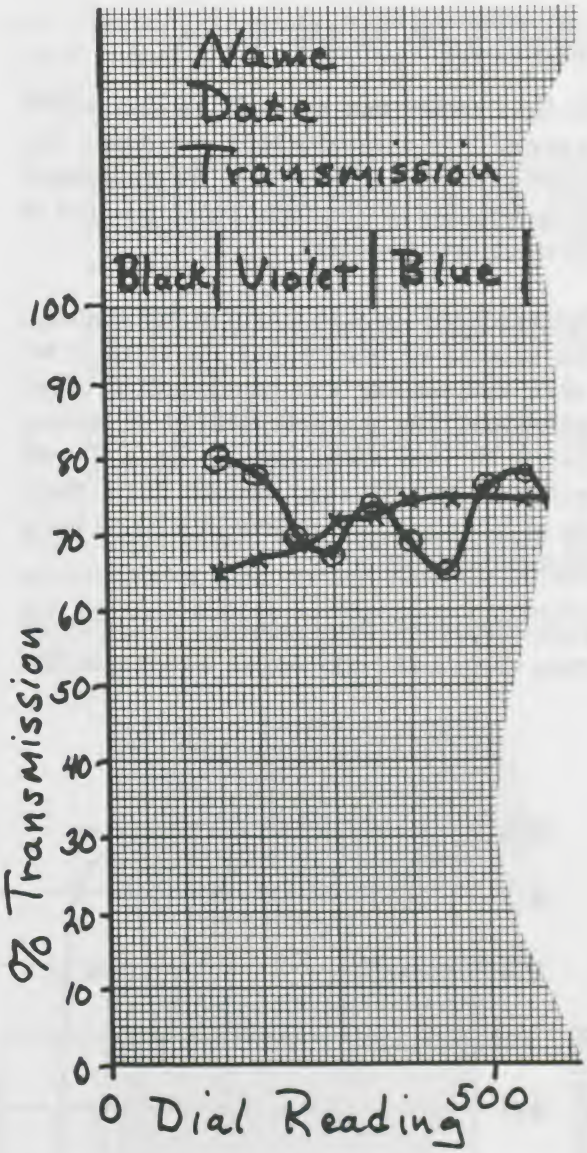


Figure 63.

For what color does each filter transmit the greatest percentage of the light? Is this exactly the color of the filter when you look at it? What color would a blue filter transmit best?

For the two filters, for what color is there the greatest difference in transmission? Why doesn't this affect the color that the filters appear to be? Or does it?

Comparing with the True Spectrum

We have stated that we shall use nanometers as our units in measuring light. But how is this done? How do you determine the wavelength in nanometers of the light being detected in the spectrophotometer?

You measured the wavelength in dial readings. The process of determining the relation between dial reading and wavelength is called *calibration.* The simplest method of calibration is to find sharp features on a known spectrum. For instance, sunlight has a sharp dip at 527 nm, and a yellow in a flame has a sharp peak at 589 nm.

Your didymium filter also has a number of sharp drops and peaks whose wavelengths are known exactly. The transmission spectrum of didymium, made by using an expensive and accurate commercial instrument, is given below.

The spectrum is like a fingerprint, which has a number of key identification points. The wavelengths of these key points can be read from the axis. Thus you can label the corresponding points on your spectrum.

1. *Compare your transmission spectrum* for didymium with the spectrum given. How many peaks and valleys on your graph can you identify which correspond to the spectrum of Figure 64?

   You should be able to identify at least the following points:

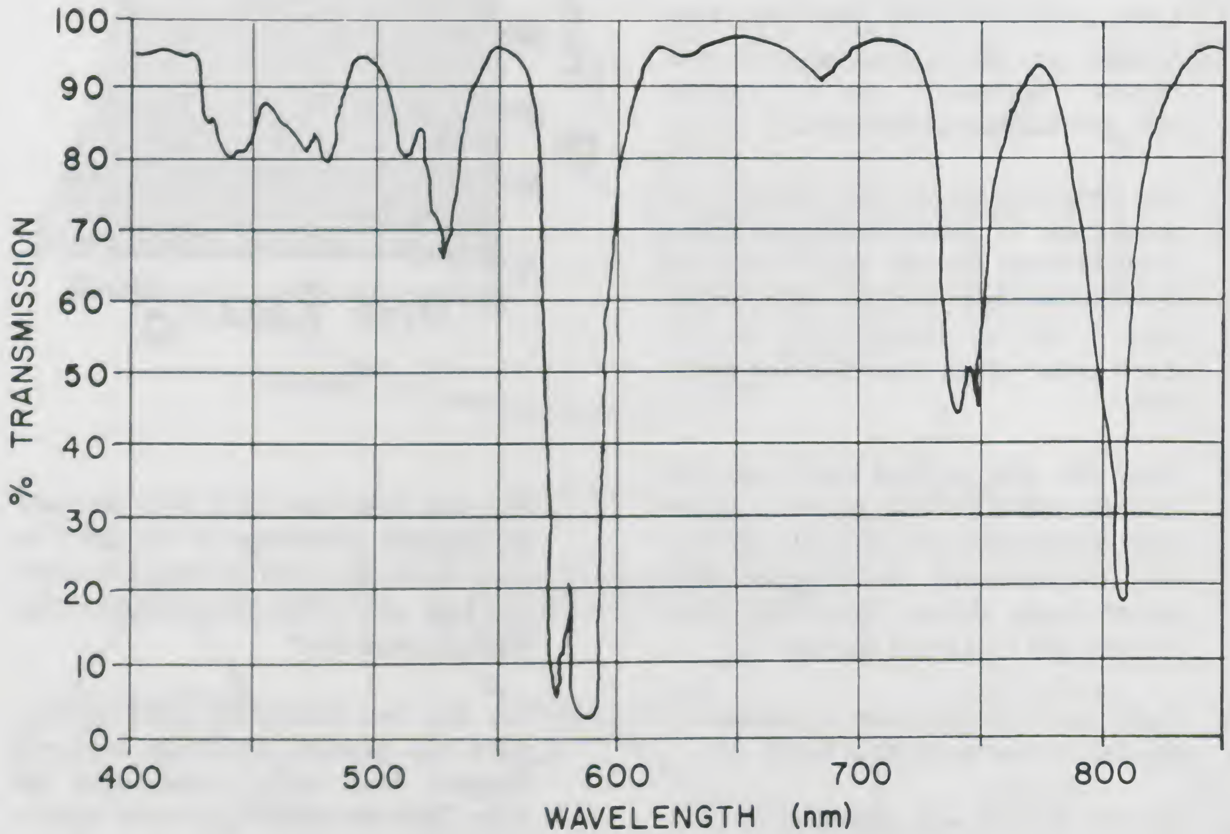


Figure 64. Transmission spectrum of didymium glass filter as taken from a Beckman DU spectrophotometer.

a. The peak which occurs at 555 nm on the green side of the large "valley."

b. The large valley, which is centered at 580 nm, in the yellow.

c. The dip centered at 685 nm in the far red.

d. The valley at 745 nm in the infra-red.

2. *Make a table* like that shown below for recording these key features.

3. *Record the wavelength* of each feature on the published spectrum and the *corresponding dial reading* on your spectrum. Record as many features as you can clearly identify.

Drawing the Calibration Graph

The purpose of calibration is so that you can translate dial readings into the corresponding wavelength of light passing through the exit slit. This will be done by drawing a *calibration graph,* which is of dial readings against wavelength.

Feature	Dial Reading	Wavelength (nm)
Peak	780	555
Large Valley	950	580
Slight Dip	1400	685
Large Valley	1670	745

1. *Label a piece of graph paper* with Dial Readings on the horizontal axis and Wavelength in nanometers on the vertical axis. See Figure 65.

2. *Plot the data points* from your identification table.

3. *Draw the best straight line* you can through your points.

From this graph you can now read the wavelength of light passing through the exit slit for any setting on the monochromator dial.

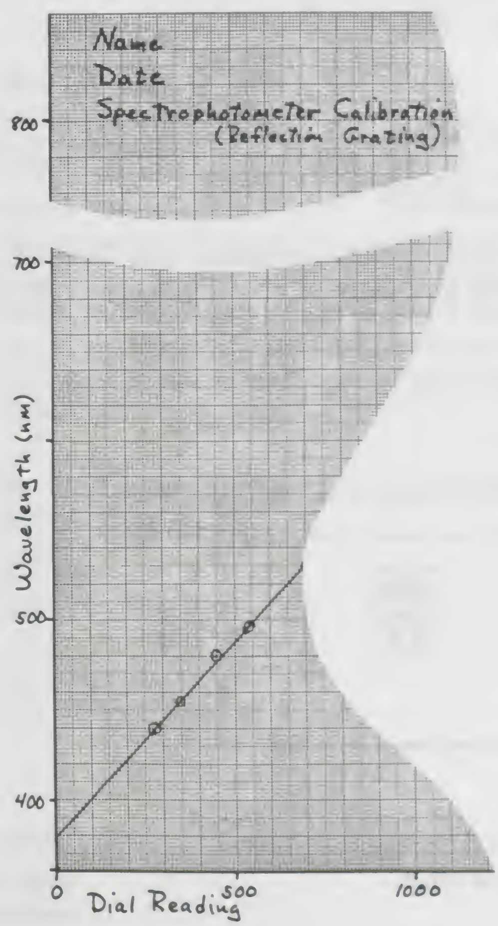


Figure 65.

Recalibration

Obtaining the calibration graph has been a somewhat lengthy process. If you accidentally bumped the apparatus you would not want to have to go through the process again to check the calibration. But you wouldn't have to. You can use your original calibration graph to recalibrate.

Here's how it works. Using the large valley in the spectrum at yellow (580 nm), you could do the following:

1. *Set the dial* at the corresponding dial reading from your calibration graph. (This is 950 in the example on the previous page.)

2. *Rotate the grating* by hand until that valley is on the exit slit.

3. *Adjust the grating* so that the valley is *exactly* centered by using the meter to indicate exactly when the minimum light is being transmitted.

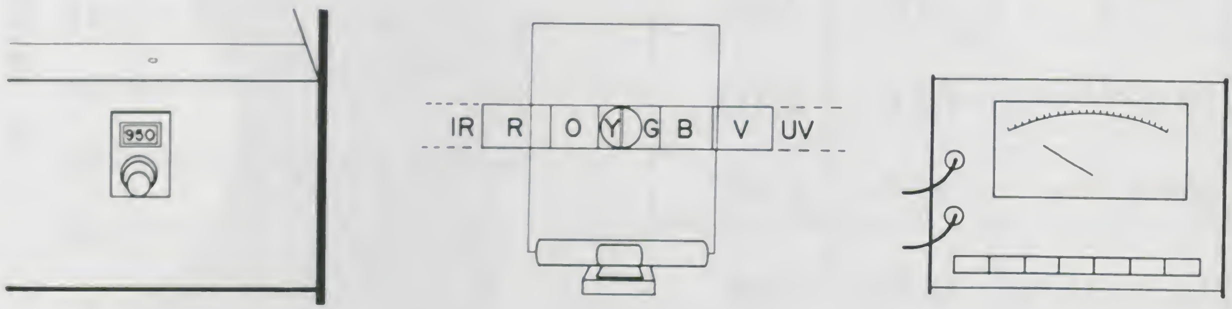
If you do this correctly, then each of the other key features should appear at the dial settings observed when you first calibrated the spectrophotometer. For instance, in the example the dip at 685 nm should occur at 1400; the valley at 745 nm, at 1670, and so on.

Optional Experiments

1. Several additional filters are supplied. Guess the transmission spectrum of each and then measure it, repeating the procedure on page 54.

2. Transparent objects do not strongly absorb light we can see. However, the spectrophotometer can measure absorption beyond the visible range. Find some transparent materials—plastic, cellophane, glass—and measure their transmission spectra. Obtain thick samples for the greatest effect. Cellophane can be made thick by folding many layers together.

3. Sunglasses are a type of filter. One extremely important function of sunglasses is to cut out harmful ultraviolet radiation. Obtain a pair of sunglasses and see if they do cut out the ultraviolet.



Dial set to the calibration-curve value.

Grating turned so that large valley in yellow is centered on exit slit.

Grating adjusted to give minimum meter reading.

Figure 66. Recalibration of the spectrophotometer.

APPLICATIONS OF SPECTROPHOTOMETERS

You have obtained the transmission spectrum for each of two filters. You might well ask what good are they and how can they be used in any practical way?

These spectra are much like fingerprints. Each substance has its own unique and characteristic pattern of absorption and transmission. There are catalogues which give thousands of such spectra taken from all kinds of substances; each spectrum is unique and identifiable with one substance. If you did not know your filter was didymium, you could have gone to one of these catalogues, found it there, and unambiguously identified it.

Qualitative Analysis

One of the most important applications of spectrophotometers is to identify substances by their transmission spectra. This is called *qualitative analysis.* It can be used to identify one substance in the presence of several others. For example, it is possible to identify tiny amounts of sodium dissolved in a complicated liquid, such as beer, because sodium has a unique absorption spectrum.

Your teacher could, in principle, mix together a solution of four or five different chemicals that you never heard of and ask you to determine which chemicals were in the solution by means of their transmission spectra. In practice, this identification would be extremely difficult. You probably would end up with a spectrum that had twenty or more peaks or valleys, and you would not know which features of the spectrum were due to which compound. Thus qualitative analysis is useful, but in practice it is limited to identifying one or two unknowns at a time.

Quantitative Analysis

One other important application of spectrophotometers is in finding out *how much* of an identified substance is present. As you recall from Section A, when you put two filters together they absorb much more light and each of the valleys in your transmission spectrum is substantially deeper. Similarly if you compare two solutions containing sodium, one with twice as much as the other, the one with twice as much sodium will absorb more light for each valley.

This is called *quantitative analysis* because you can determine the *quantities* of unknown substances that are present. Quantitative analysis has many chemical and medical applications. For instance, one can determine accurately the amount of sugar in blood from the spectrum of a small sample. Knowledge of the amount of sugar in the blood is important for diabetics.

On the next page qualitative and quantitative analysis are compared.

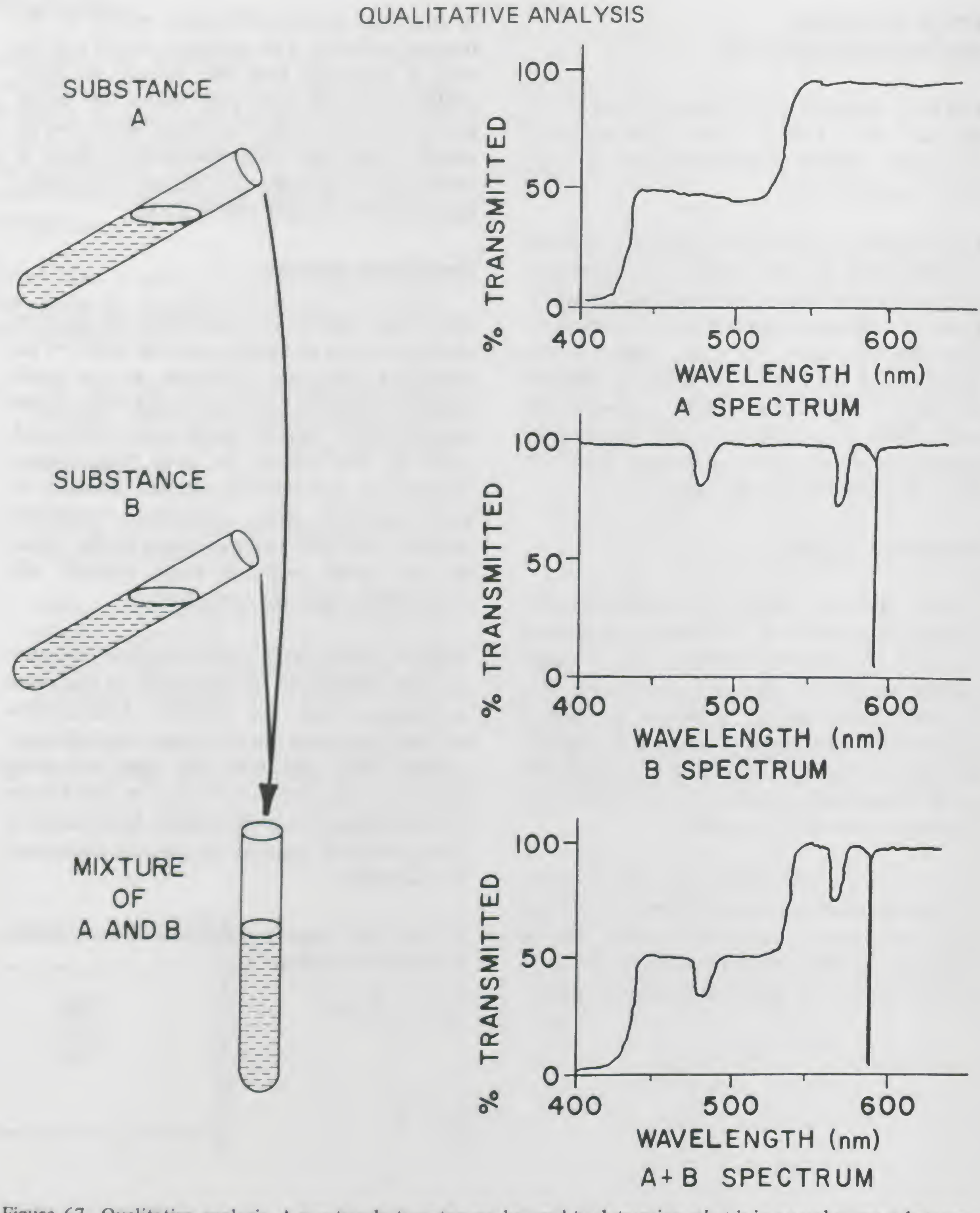
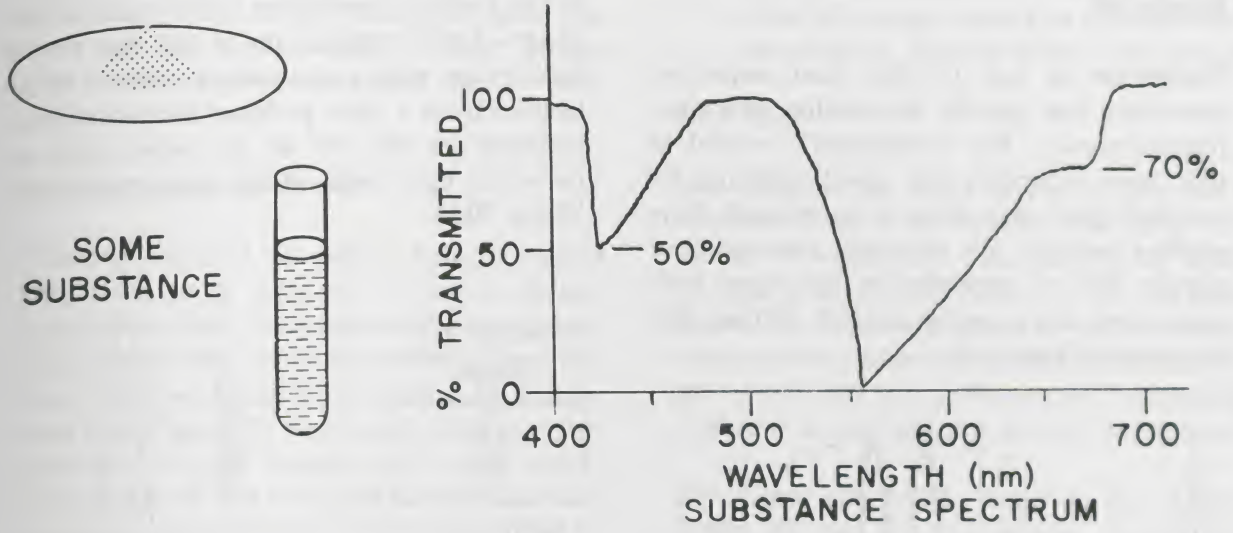


Figure 67. Qualitative analysis. A spectrophotometer can be used to determine *what* is in an unknown substance. Each substance has its own unique spectrum as shown in the drawings. Even when two substances are mixed each individual substance can be identified in the spectrum of the mixture. For instance, A's two edges at 435 nm and 530 nm can be seen in the mixture's spectrum. Also the three absorption maxima from B at 481 nm, 569 nm, and 590 nm can be seen in the mixture's spectrum. Actually,the sharp spike in the spectrum of substance B (at 590 nm) can be seen to consist of two closely spaced absorption maxima by using a better spectrophotometer.



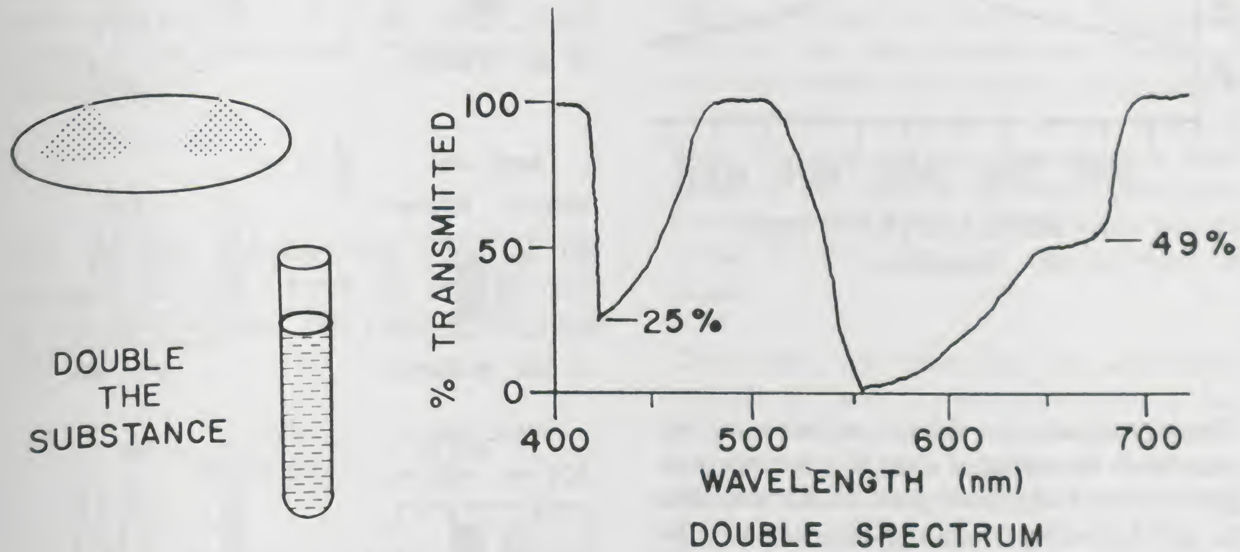


Figure 68. Quantitative analysis. A spectrophotometer can be used to determine *how much* of a substance is present. The more that is present, the more light it will absorb. Recall the experiment and discussion of Section A in which the number of filters in the light beam was doubled. Similarly, the amount of light absorbed at a particular wavelength can be used to determine the *quantity* of any substance that is present in a given sample. For example, in the top sketch there is a valley at 420 nm representing 50% absorption. In the lower portion of the sketch, twice as much of the same material is present in the solution. Thus, an additional 50% of the 50% is absorbed, so that only 25% is transmitted at the 420-nm valley. The locations of the spectral features have not changed, only their depths.

SPECTROPHOTOMETER QUALITY

Resolution

Resolution is one of the most important quantities that specify the quality of a spectrophotometer. The instrument's resolution tells how accurately the spectrophotometer can distinguish one color or wavelength from another nearby. For example, suppose your sample had a transmission spectrum with some very sharp peaks around 600 nm like the graph of Figure 69.

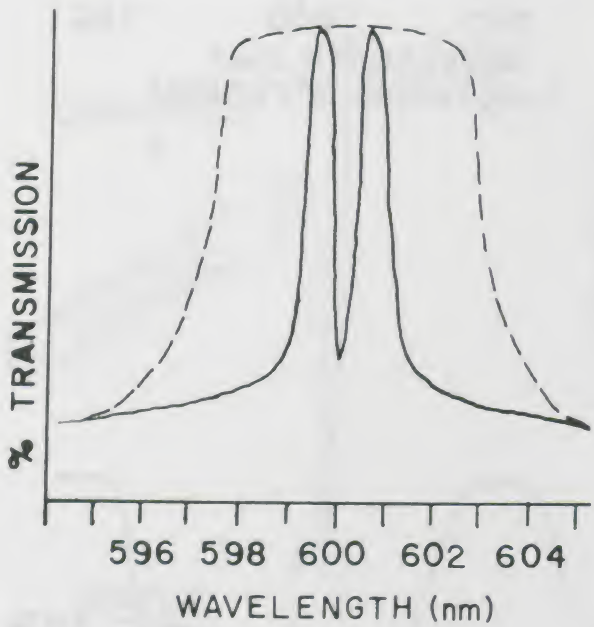


Figure 69.

These peaks are less than 1 nm wide and are separated by about 1 nm. If your spectrophotometer had a resolution of 0.1 nm, then it could *resolve* or distinguish between the two peaks. The transmission spectrum that it gave would be much like that shown.

However, if its resolution was 5 nm, then the spectrophotometer would not be able to separate the two peaks. The result would be a transmission spectrum like the dashed line.

The Basis of Resolution

A key factor in resolution is the width of the image of the entrance slit at the exit slit. A light beam with an extremely narrow wavelength (from a laser perhaps) would make a rectangle on the exit slit the same width as the white light image of the entrance slit (see Figure 70A).

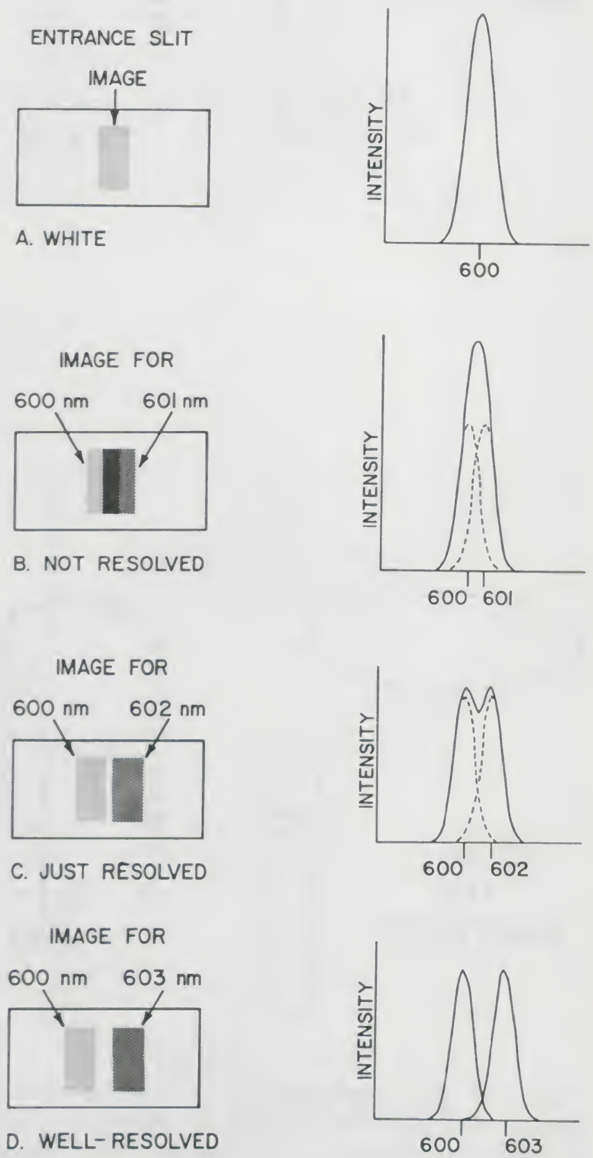


Figure 70. Resolution of spectral lines. The graphs on the right represent the spectra as produced in a spectrophotometer. The images on the left are an approximation, with sharp edges.

Two narrow wavelength beams that are close together cannot be distinguished, or resolved, if their images overlap as in B. The two can be just resolved if their images don't quite touch, as in C, and they are well resolved in D.

Calculating the Resolution

These pictures of slit images help to explain resolution as a measure of the wavelength separation that the spectrophotometer can distinguish. But we must translate these pictures into wavelengths. According to illustration C of Figure 70, two wavelengths are "just resolved" if their images don't quite touch. The widths of the two images determine how close they can come before they touch.

The wavelengths for which the images just touch are determined by how widely the colors have been separated; that is, by the dispersion. Therefore the resolution depends on both the width of the image of the entrance slit *and* the dispersion. Mathematically, the resolution R is the width of the image of the entrance slit W divided by the dispersion D.

$$R = \frac{W}{D}$$

For example, suppose the image of the entrance slit is $W = 5$ mm and the dispersion is $D = 0.25$ mm/nm. This yields a resolution of:

$$R = \frac{5 \text{ mm}}{0.25 \text{ mm/nm}} = 20 \text{ nm}$$

Therefore the spectrophotometer could resolve peaks in the transmission spectrum whose separation is 20 nm.

Calculate the resolution for your spectrophotometer system using your measured slit image width and the dispersion measured in Section B for that system.

Slit Width

The width of the image of the entrance slit is determined by two factors: the *actual* entrance slit width, and the ability of the optics to make a clear, narrow image of it. The latter has to do with such things as optical aberrations, surface flatness, and so on. (These topics are covered in other Physics of Technology modules, so we will not go into them here.)

The actual slit width, however, is a crucial design factor in determining spectrophotometer resolution. With perfect optics, the *image* of the entrance slit should be identical in size and shape to the *actual* entrance slit. Then, from our analysis, we see that *the narrower the entrance slit, the greater the resolution.*

As you decrease the size of the entrance slit, however, you also decrease the intensity of light that enters the monochromator and that is ultimately transmitted to the detector. Since the *range* of the instrument is determined by the range of wavelength over which the detector can read 100%, when you decrease the slit width you also decrease the range.

Thus range and resolution are interrelated; increase one and you decrease the other. And both are determined by slit width. Spectrophotometer designers must select a slit width which strikes the right balance between range and resolution. In some instruments the slit width can be changed so that the operator can vary the range and resolution to meet his specific needs.

SPECTROPHOTOMETER SPECIFICATIONS

Specs (or *specifications*) give the details of the quality of instruments. It is often hard to understand spec sheets because of the special words they use. But now that you understand the principles behind the behavior of monochromators, you should be able to figure out most of them. Two typical spec sheets are given on these pages. You should do all right on some of the specifications, but others need explanation. These explanations have been added.

READABILITY vs ACCURACY: You may be able to read the dial to within 1 nm but that reading may not actually be the correct wavelength. This says it will be right to within 2.5 nm.

SPECTRAL SLIT WIDTH: The actual slit width is not 20 nm. Instead, its width is such that the resolution is 20 nm.

PHOTOMETRIC ACCURACY vs REPRODUCIBILITY: No meter is perfectly accurate. This spec says that if the output meter reads 50% transmission the actual transmission is probably somewhere between 47.5% and 52.5% (i.e., 50 ± 2.5%). If you repeat the measurement you will get between 49% and 51%, but the accuracy is still only ± 2.5% of your best average measurement.

wavelength range	340-950 nm
wavelength accuracy	2.5 nm
wavelength readability	1 nm (1/5 division)
spectral slit width	20 nm nominal, constant over entire range
photometric accuracy (linearity)	±2.5 percent of full scale
photometric reproducibility	± 1 percent of full scale
monochromator	reflectance grating, 600 grooves /mm
regulation	± 1 percent T for line voltage change from 105-125 V, or 210-250 V with step-down transformer (transistorized model)
readout	meter, 9 cm mirrored scale calibrated in percent transmittance and 'absorbance' units
detectors	standard phototube 340-625 nm accessory phototube with red filter 625-950 nm accessory phototube with filter 380-715 nm

REGULATION: The voltage of household electricity often varies widely depending on the total area demand. This drastically affects the amount of light emitted by the source, which in turn affects the amount of light detected. Since these variations have nothing to do with the sample, they cause errors. All this is fixed by a voltage regulator which steadies the voltage supplied to the lamp. Here, a line voltage change from 105 V to 125 V would only cause a 1% error in measured transmission (T).

DETECTORS: Different detectors are required for different wavelength ranges. This tells which detector (and any additional filters) must be used for different wavelength regions.

Figure 71A. Courtesy of Bausch & Lomb, Analytical Systems Division, Rochester, New York.

RESOLVING POWER: The best resolution possible with the narrowest slit.

STRAY LIGHT: Sometimes light other than the desired color can get to the detector, causing errors, particularly when transmission is low.

The Monochromator unit consists of the optical system, mechanical drive, and electric motors that operate on signals from the electronic Control Unit.

Type of Mount	Single-pass Czerny-Turner mounting with folding mirrors to provide entrance and exit beams on a common optic axis.
Aperture Ratio	f/6.8 at 2000 angstroms.
Focal Length	350 millimeters.
Resolving Power	Better than 1 angstrom. Line-profile half-width less than 0.5 angstrom.
Stray Light	0.1% or less within $\pm 1\frac{1}{2}$ bandwidths of a given line.
Wavelength Range	Zero order to 10,000 angstroms, first order, with 1180 line/mm grating. Usable range with standard 1P28A detector, limited by air cutoff and detector sensitivity, is 1900 angstrom to 7000 angstrom. Lower limit may be extended to below 1800 angstrom by flushing the optical path with dry nitrogen . . . upper limit by use of other available detectors.
Wavelength Accuracy	Relative error ± 1 angstrom throughout usable wavelength range.
Wavelength Resettability	± 0.1 angstrom on the basis of resetting on the maximum of a narrow emission line, with photo-detected recorder output as indicator.
Reciprocal Dispersion	Approximately 20 angstrom/mm at exit slit with 1180 lines/mm grating.
Grating	Precision plane grating replica; 48 mm x 48 mm ruled area. Standard grating of 1180 lines/mm, blaze wavelength 2500 angstroms. (Gratings of other line spacing and blaze will be made available in the future.)
Mirrors	Aluminized first-surface mirrors with MgF_2 over-coating. Optical surfaces corrected to ¼-wave mercury green line.
Collimating and Focusing	50 mm diameter, parabolic, 350 mm focal length.
Folding	25 mm x 35 mm plane.
Slits	Ground and polished straight knife edges, bi-laterally adjustable; entrance and exit slit-width ganged to single control.
Width	Continuously variable between 5 and 2000 microns. A 4-digit counter reads directly in microns.
Height	12 mm maximum; provision for intermediate heights of 0.5, 1, and 3 and 5 mm.
Wavelength-Scan Mechanism	Sine-bar and precision lead-screw assembly driven by precision stepping motor. A 5-digit counter reads directly in angstroms. Fractional scale of 0.2 angstrom divisions permits readability of 0.1 angstrom.

RECIPROCAL DISPERSION: This is dispersion, as we have used the word. Moving the spectrum at the exit slit one millimeter changes the wavelength getting through by 20 Å.

WIDTH: This counter reads the actual slit widths.

BLAZE WAVELENGTH: The blaze improves the light intensity around one particular angle. This angle corresponds to 2500 Å here.

Figure 71B. Copyright 1968 Heath Company, Reprinted by permission of Heath Company.

OTHER SPECTROPHOTOMETER SYSTEMS

The spectrophotometer you have worked with is similar to many actual laboratory instruments. That particular arrangement of optical components is called the *Czerny-Turner mount,* after its inventors.

But there are many other arrangements which can accomplish the same result. For instance, we can substitute lenses for the spherical mirrors, and a prism or transmission grating for the reflection grating. The results produce monochromators that look different but operate the same.

We will examine here commercial versions of these not-so-different monochromators. And we will suggest component arrangements you can make on your spectrophotometer that will be essentially the same as for some commercial instruments. Each system can be assembled and calibrated using the transmission spectrum of didymium by following the procedures outlined for the reflection grating spectrophotometer.

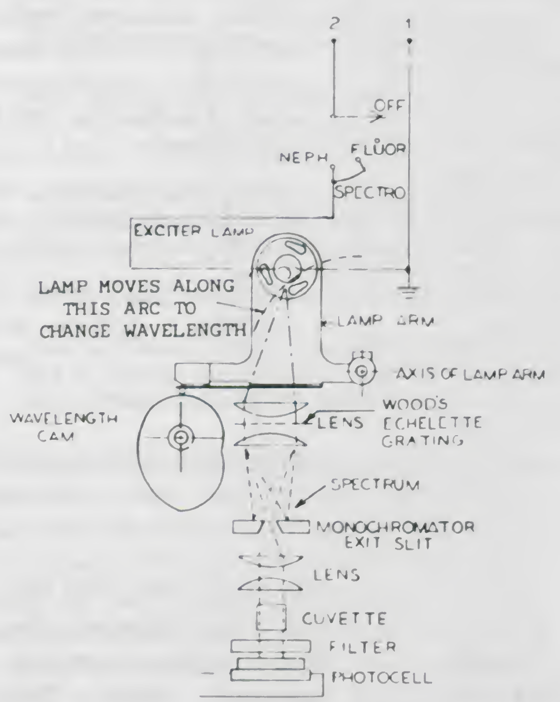


Figure 72. A commercially made spectrophotometer using a transmission grating and lenses. Photo courtesy of Coleman Instruments Division of the Perkin-Elmer Corporation.

Transmission Grating Spectrophotometers

The optics of a monochromator using a transmission grating is quite simple. Lenses are often used with transmission gratings because the lenses can be placed very close to the grating.

This design is utilized in the inexpensive commercial unit illustrated in the diagram of Figure 72. This is the Coleman Junior Spectrophotometer. It uses a transmission grating as the dispersive element, and the spectrum is scanned past the exit slit by moving the light source with a specially designed and calibrated wavelength cam.

How to Build One

Figure 73 shows how to build a transmission grating spectrophotometer on your lab apparatus. This system uses spherical mirrors rather than lenses to collimate and focus the light. But, if you are inventive, you can probably find a way to use lenses. In this system, the spectrum is scanned across the exit slit by rotating the flat mirror with the digital dial.

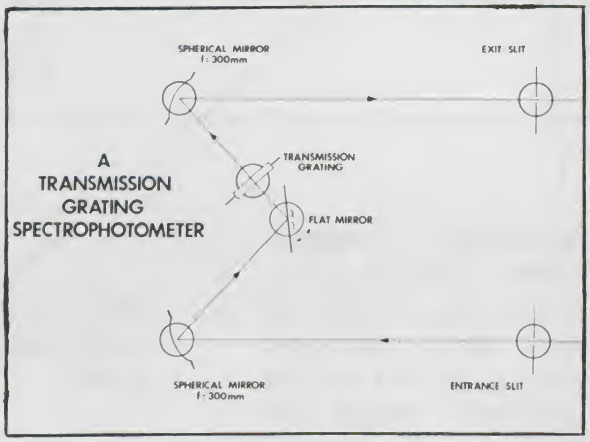


Figure 73.

Prism Spectrophotometers

One of the shortcomings of prisms is their low dispersion over most of the spectrum. The dispersion can be doubled by passing light through the prism twice. This is accomplished by placing a mirror just in back of the prism. This arrangement is called the *Littrow mount.* It is illustrated in Figure 74.

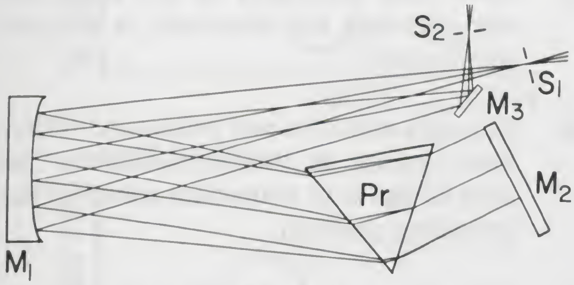


Figure 74.

The Littrow mount is actually used in many commercial spectrophotometers. The drawing is a diagram of the monochromator from an actual instrument. See if you can follow the light path from the entrance slit S_1 to the exit slit S_2. The spectrum is scanned across the exit slit by rotating mirror M_2.

How to Build One

The Littrow mount is difficult to set up on your spectrophotometer because the exit beam is reflected back along the entrance beam. As a result the two slits must be quite close together. Therefore, you might be content to use a prism without reflecting the beam back through the prism for a second pass. This is not a Littrow mount. But you can set up the Littrow system to verify and understand its behavior.

Two different systems are shown in the diagrams of Figures 75 and 76, one using lenses and one using spherical mirrors to collimate and focus the light.

One interesting feature of these layouts is that they can be easily aligned. By removing the

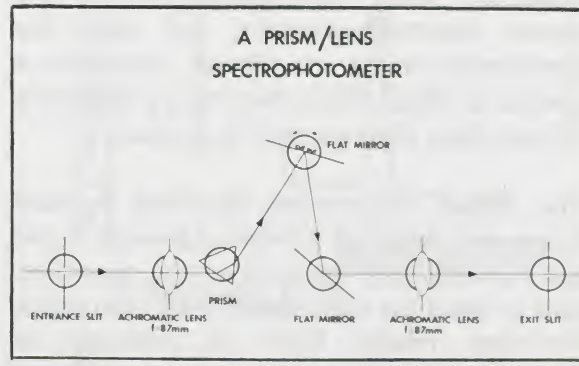


Figure 75.

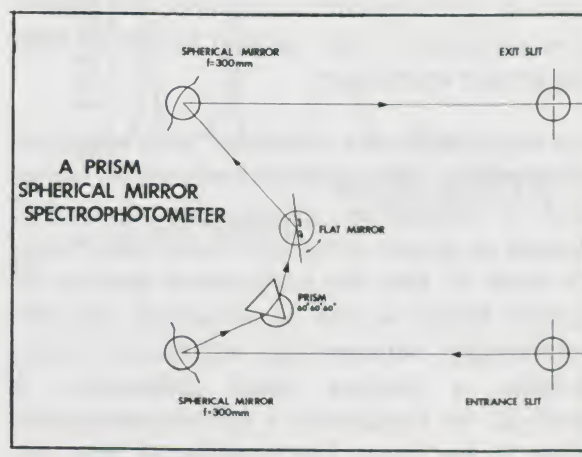


Figure 76.

prism and the flat mirror, the lenses should focus a white image of the entrance slit onto the exit slit.

When you replace the prism you may notice that the image of the spectrum is curved. This is always a problem with prism spectrophotometers. Since it cannot be solved easily most designers use slightly curved slits. Since we do not have curved slits we must take a loss in resolution as a result.

REVIEW

Summary

In Section C you have examined the optical components of a spectrophotometer. You assembled those components into an improved spectrophotometer, and used that spectrophotometer to obtain transmission spectra of filters. There was then a discussion of how these ideas are used in practice.

The optical components discussed included lenses and spherical mirrors. Although lenses use refraction and spherical mirrors use reflection to bend the light beams, they accomplish the same results. Both can collimate, or render parallel, rays of light which are diverging from a point, and both can collect or focus parallel light to a point. These are their uses in spectrophotometers since the dispersive elements require parallel beams of light for proper operation.

An experiment was performed with a spectrophotometer, using spherical mirrors for optics and a diffraction grating for dispersion. Lenses or prisms could have been substituted. In order to find the transmission spectra for certain filters we had to accurately find the relationship between dial settings and wavelengths, a process called *calibration.* A method to recalibrate a spectrophotometer after it has once been calibrated was discussed.

The experiment of this section illustrated the uses and construction of commercial spectrophotometers. Just as they can be used to identify a filter, spectrophotometers can identify compounds. This is *qualitative analysis.* Spectrophotometers can also be used for *quantitative analysis,* determining the amounts of known chemicals present. The specifications, or specs, of commercial spectrophotometers were discussed.

QUESTIONS

1. List five optical elements commonly found in spectrophotometers.
2. What is the function of each element listed in the previous question?
3. What is the process by which a lens bends light beams? What other spectrophotometer optical element uses this principle?
4. Why does resolution depend upon slit width?
5. State four properties of the dispersive elements that are important in spectrophotometers.
6. Compare and constrast prisms and reflection gratings on their performances for each of the four properties stated in the preceding question.
7. Why do you think slits are used in spectrophotometers instead of:
   a. large holes
   b. small holes
   c. any other pattern such as a cross
8. Is it possible to use a single transmission spectrum from a spectrophotometer for both qualitative and quantitative analysis at the same time? Explain your answer.
9. Where in the path of light through a spectrophotometer is the best place for the sample? Should it be before the first slit, just after it, near the exit slit, or somewhere else? Does it make any difference? Why?
10. Set up a spectrophotometer, using a prism and lenses. Measure the resolution and dispersion. In what ways is this spectrophotometer better or worse than the one you assembled before?
11. Suppose you were going to manufacture precision visible-range spectrophotometers. What improvements would you desire to make in the spectrophotometer you used before you would sell it commercially? How would you accomplish these improvements?

12. Suppose that the graphs for substances A, B, and C are precision spectra from a handbook. The unknown is most likely which of these substances? Explain the imperfect match.

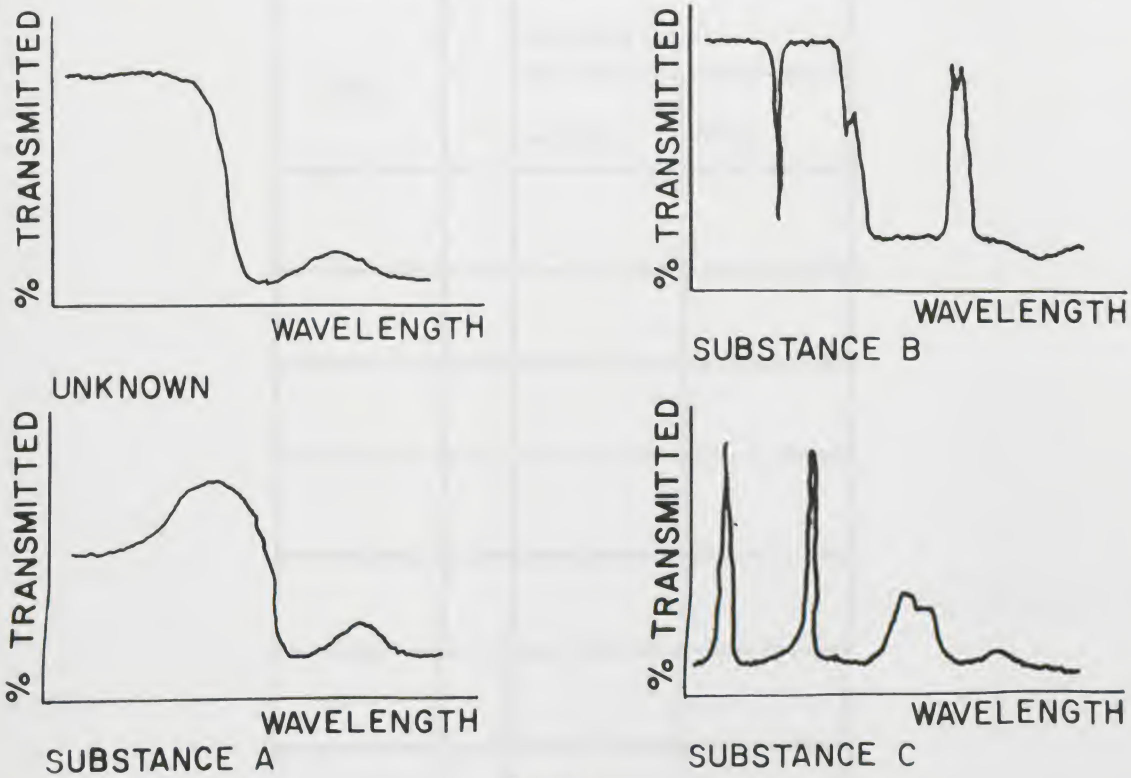


Figure 77.

COMPUTATION SHEET

DATA PAGE

EXPERIMENTS B-1 and B-2: Measuring the Grating and Prism Spectra

Color		Distance (mm)	
		Grating	Prism

DATA PAGE

EXPERIMENT B-3. Comparing a Prism and a Grating

	Prism	Grating

CALCULATING DISPERSION:

Wavelength	Grating Experiment B-1	Prism Experiment B-2	Grating Experiment B-4
400 nm			
550 nm			
700 nm			

DATA PAGE

EXPERIMENT B-4. A Better Spectrophotometer

Color		Distance (mm)
		Grating

DATA PAGE

EXPERIMENT C-1. Measuring Transmission Spectra

Width of entrance slit:

Width of exit slit:

Width of entrance slit image:

(Make Table Here)

0-07-001731-X